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Combined cooling, heating and power systems: A survey ☆

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ABSTRACT

The combined cooling, heating and power (CCHP) system – a typical representative of the decentralized energy system – has been increasingly attracting attention in academia and industries in recent years, thanks to its distinctive advantages of high system and economic efficiency, and less greenhouse gas (GHG) emissions. In this paper, the state of the art of CCHP research is surveyed. First, the development and working scheme of the CCHP system will be presented. Some analyses of the advantages of this system and a brief introduction of the related components are then given in the first part. In the second part of this paper, we elaborately introduce the prime mover and thermally activated facilities. Recent research progress on the management, control, system optimization and sizing will be summarized in the third part. The development of the CCHP system in representative countries and the development barriers will be discussed in the last part.

Contents

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1. Introduction

With the rapid development of distributed energy supply systems [1–4], combined heating and power (CHP) systems and combined cooling, heating and power (CCHP) systems have become the core solutions to improve the energy efficiency and to reduce greenhouse gas (GHG) emissions [5–9]. The CCHP system is an extended concept of the CHP system, which has been widely utilized in large-scale centralized power plants and industrial applications [10]. CHP systems are developed to conquer the problem of low energy efficiency of conventional separation production (SP) systems. In SP systems, electric demands, which include daily electricity usage and electric chiller usage, and heating demands are provided by the purchased electricity and fuel, respectively. Since no self-generation exists in SP systems, they are proved to be of low efficiency; however, in CHP systems, most of the electric and heating demands are provided simultaneously by a prime mover together with a heat recovery system, a heat storage system, etc. Energy demands beyond the system capacity can be supplied by the local grid and an auxiliary boiler. If introducing some thermally activated technologies, e.g., absorption and adsorption chillers, into the CHP to provide the cooling energy, the original CHP system evolves to be a CCHP system [11], which can also be referred to as the *trigeneration* system and building cooling heating and power (BCHP) system. Since there is no need for cooling energy from cooling system generally in winter, the CHP system can be regarded as a special case of the CCHP system. A CCHP system can achieve up to 50% greater system efficiency than a CHP plant of the same size does [12].

A typical CCHP system is shown in Fig. 1. The power generation unit (PGU) provides electricity for the user. Heat, produced as a by-product, is collected to meet cooling and heating demands via the absorption chiller and heating unit. If the PGU cannot provide enough electricity or by-product heat, additional electricity and fuel need to be purchased to compensate for the electric gap and feed the auxiliary boiler, respectively. In this way, three types of energy, i.e., cooling, heating and electricity, can be supplied simultaneously.

Compared with conventional generating plants, the advantages of a CCHP system appear in three-fold: high efficiency, low GHG emissions and high reliability.

First, the high overall efficiency of a CCHP system implies that less primary fuel is consumed in this system to obtain the same amount of electric and thermal energy. In [10], the authors give an example to show that, compared with the traditional energy supply mode, the CCHP system can improve the overall efficiency from 59% to 88%. This improvement owes to the cascade utilization of different energy carriers and the adoption of the thermally activated technologies. As the main electricity source, the PGU has an electric efficiency as low as 30%. By implementing the heat recovery system, the CCHP system can collect the by-product heat to feed the absorption/adsorption chiller and heating unit to provide cooling and heating energy, respectively. By adopting the absorption chiller, no additional electricity needs to be purchased from the local grid to drive the electric chiller in summer, but only the recovered heat is used. In winter, a CCHP system degenerates to be a CHP system. The high efficiency of the CHP system is investigated in [13–20]. In a nutshell, a CCHP system can dramatically reduce the primary consumption and improve the energy efficiency.

The second advantage involved in the CCHP system is the low GHG emissions. On the one hand, the trigeneration structure of the CCHP system contributes to this reduction. Compared with SP systems, if within the capacity limitation of the prime mover, no additional electricity needs to be purchased from the local grid, which is supplied by fossil-fired power plants. It is well known that, even though the penetration of some types of renewable energy, e.g., the wind, tide and solar energy, increases significantly

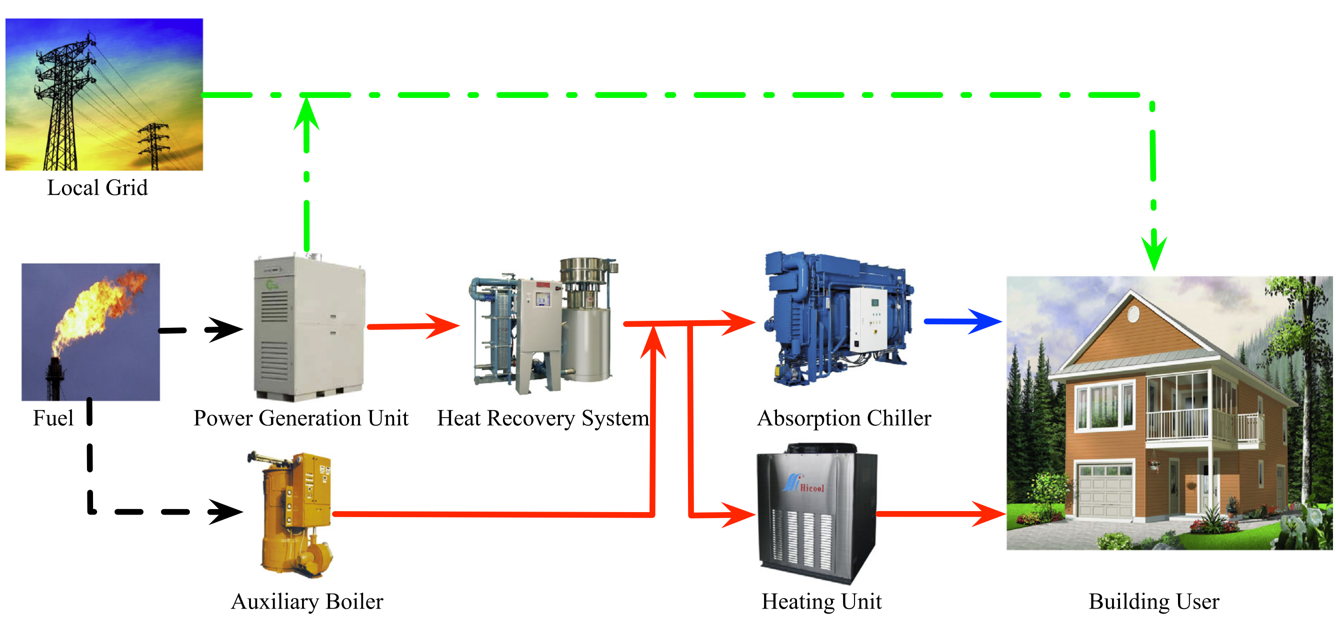

Fig. 1. A typical CCHP system.

[21–23], because of their intermittency, the main electricity producer is still the fossil-fired power plant. By reducing the consumption of electricity from the local grid, GHG emissions from fossil-fired power plants can be decreased. Moreover, adopting the thermally activated technologies can also reduce the electricity consumption by the electric chiller, which will result in less consumptions of fossil fuel in the grid power plant. On the other hand, new technologies in the prime mover also contribute to the GHG emissions reduction. Incorporating fuel cells, which are one of the hottest topics in recent years, in the CCHP system can increase the system efficiency up to 85–90% [24]. Compared with some conventional prime movers, such as the internal combustion (IC) engine and combustion turbine, the new-tech prime movers can provide the same amount of electricity with less fuel supply and less GHG emissions. In recent years, aiming to reduce the GHG emissions, an increasing number of countries begin to run the carbon tax act [25–29]. As a result of these acts, reducing GHG emissions can not only reduce the contaminant of the air, but also can improve the system economic efficiency.

The other benefit brought by the CCHP system is the reliability, which can be regarded as the ability to guarantee the energy supply at a reasonable price [30]. Recent cases have demonstrated that the centralized power plants are vulnerable to natural disasters and unexpected phenomenon [31]. Changes in climate, terrorism, customer needs and electricity market are all fatal threats to the centralized power plants [10]. The CCHP system, which adopts the distributed energy technologies, can be resistant to external risks and has no electricity blackouts, for its independency on electricity distribution. A comparison of the reliability between the distributed and centralized energy systems in Finland and Sweden can be found in [30].

A typical CCHP system consists of a PGU, a heat recovery system, thermally activated chillers and a heating unit. Normally, the PGU is the combination of a prime mover and an electricity generator. The rotary motion generated by the prime mover can be used to drive the electricity generator. There are various options for the prime mover, e.g., steam turbines, stirling engines, reciprocating IC engines, combustion turbines, micro-turbines and fuel cells. The selection of the prime mover depends on current local resources, system size, budget limitation and GHG emissions policy. The heat recovery system plays a role in collecting the by-product heat from the prime mover. The most frequently used thermally activated technology in the CHP/CCHP system is the absorption chiller. Some novel solutions, such as the adsorption chiller, and the hybrid chiller, are also adopted in CCHP systems [32–36]. The selection of heating unit depends on the design of the heating, ventilation and air conditioning (HVAC) components.

With the benefits of high system and economic efficiency, and less GHG emissions, CCHP systems have been widely installed in hospitals, universities, office buildings, hotels, parks, supermarkets, etc. [37–41]. For example, in China, the CCHP project at Shanghai Pudong International Airport generates combined cooling, heating and electricity for the airport's terminals at peak demand times. It is fuelled by natural gas from offshore in the East China Sea [42]. This system is equipped with one 4 MW natural gas turbine, one 11 t/h waste heat boiler, cooling units of four YORK OM 14,067 kW, two YORK 4220 kW, four 5275 kW steam LiBr/water chillers, three 30 t/h gas boilers and one 20 t/h as standby for heat supply [43]. In the last decade, the installation of CCHP systems grows flatly. Especially, the development is much slower in developing countries than that in developed countries due to the following barriers: less public awareness, insufficient incentive policies and instruments, nonuniform design standards, incomplete connections with power grid, high price and supply pressure of natural gas, and difficulties in manufacturing equipment [43]. According to a survey provided by the World Alliance for Decentralized Energy (WADE), the penetration of CCHP systems can be enlarged by introducing of European Union Emissions Trading Scheme (EUETS) and increasing carbon tax.

This survey paper aims to provide some fundamental information and the state of art of CCHP systems. Analyses and comparisons of system components, suitability scope, operating economy, system configurations and operation strategies are given for the purpose of engineering assessment. This paper is organized as follows: in Section 2, different prime movers for driving the CCHP systems are introduced and compared; three main thermally activated technologies that can be used in CCHP systems to achieve energy cascade utilization are introduced in Section 3; Section 4 focuses on different system configurations according to the system capacity; in Section 5, conventional and novel operation strategies, and system optimization methods are introduced, analyzed and compared; development of CCHP systems in three main countries are discussed in Section 6; Section 7 concludes this paper.

2. Prime movers

A prime mover, defined to be a machine that transforms energy from thermal, electrical or pressure form to mechanical form, typically an engine or turbine, is the heart of an energy system. Normally, the output of a prime mover is the rotary motion, so it is always being used to couple with an electric generator. In recent years, the mostly installed prime movers are gas engines and gas turbines [44]. These two types of prime movers belong to the reciprocating IC engine and the combustion turbine/micro-turbine. Some other types of prime movers, such as steam turbines, micro-turbines, stirling engines and fuel cells, are also being used in CCHP systems in some particular cases. In this section, emphasis will be put on reciprocating IC engines and combustion turbines/micro-turbines; other types will also be discussed.

2.1. Reciprocating internal combustion engines

A reciprocating engine, also known as a piston engine, is a heat engine that uses one or more reciprocating pistons to convert pressure into a rotary motion [45]. There exist two types of reciprocating engines, i.e., spark ignition, which uses the natural gas as the preferred fuel and can also be fed by the propane, gasoline or landfill gas, and compress ignition, which can operate on diesel fuel or heavy oil [46]. The size of the reciprocating engines can range from 10 kW to over 5 MW.

As stated in [47,48], with the advantages of low capital cost, quick starting, well load following, relatively high partial load efficiency and generally high reliability, the reciprocating engines have been widely used in many distributed generation applications, such as the industrial, commercial and institutional facilities for power generation, and CCHP systems. The waste heat of the reciprocating engine, consisting of exhaust gas, engine jacket water, lube oil cooling water and turbocharger cooling [46], can be used in thermally activated facilities in the CCHP system. This energy cascade utilization can efficiently improve the system efficiency. However, a reciprocating engine does need regular maintenance and service to ensure its availability [49]. Since the rising level of GHG emissions has become a big concern, applications of diesel fueled engines are restricted for the high emission level of NO_x. Current natural gas ignition engines have relatively low emissions profiles and are widely installed. One example is that HONDA has developed a new cogenerator, which is a natural gas-powered engine, powered by “GF160V”. This cogeneration unit can reduce the CO_2 emissions up to approximately 20% [50]. Another classical application of the reciprocating engine example

is the CHP plant with IC engines installed at the Faculty of Engineering of the University of Perugia since 1994 [51]. The experiment results show that by introducing the absorption cooler into the plant can dramatically reduce the payback period.

Reciprocating IC engines are quite popular in some applications when working together with an electric or absorption chiller. High temperature exhaust gas from the engine can be used to provide heating and cooling, or to drive the desiccant dehumidifier. Maidment et al. [40] analyze a CCHP system for a typical supermarket using a gas turbine and a LiBr/water absorption chiller. They discuss the methodology for choosing the prime mover between a gas engine and a gas turbine. The result shows that this CCHP system offers significant primary energy consumption savings and CO_2 savings compared to conventional heat and power schemes. In [52], the authors assess a CCHP system, which is driven by a reciprocating IC engine, combined with a desiccant cooling system. This system incorporates a desiccant dehumidifier, a heat exchanger, and a direct evaporative cooler. The parametric analysis provided in this work shows that combining the desiccant cooling system can handle both latent and sensible loads in a wide range of climate conditions. The COP of this system is 1.5 times than the conventional system. Longo et al. [53] discuss a CCHP system equipped with an Otto engine and an absorption machine. The exhaust thermal energy is recovered to drive a double-effect LiBr/water cycle, and the heat recovered from the cooling jacket is used to drive a single-effect LiBr/water cycle. In [54], Talbi et al. explore the theoretical performance of four different configurations of a CCHP system equipped with a turbocharger diesel engine and an absorption refrigeration unit. The results show the potential of using a diesel absorption combined cycle with pre-inter cooling to achieve higher power output and thermal efficiency among other configurations. The situation of CO_2 emissions of CCHP systems with gas engines under different working conditions is discussed in [55].

2.2. Combustion turbines

The combustion turbine, also known as the gas turbine, is an engine in which the combustion of a fuel, usually the gas, occurs with an oxidizer in a combustion chamber [56]. Combustion turbines have been used for the purpose of electricity generating since 1930s. The size of gas turbines ranges from 500 kW to 250 MW, which makes it suitable for large-scale cogeneration or trigeneration systems. At partial load, the efficiency of the gas turbine can be unacceptable lower than full-capacity efficiency. As a result, generation sets smaller than 1 MW are proven to be uneconomical [10]. Gas turbines also produce high-quality (high-temperature around 482 °C) exhaust heat that can be used by thermally activated processes in CCHP systems to produce cooling, heating or drying, and to raise the overall system efficiency to approximately 70–80% [57]. Adopting some cycle integration technologies, such as steam injection gas turbines and humid air turbines, can improve the performance of the simple-cycle gas turbine by integrating the bottoming water/steam cycle into the gas turbine cycle in the form of water or steam injection [58].

For GHG emissions, because of the use of natural gas, when compared with other liquid or solid fuel-fired prime movers, gas turbines can dramatically reduce CO_2 emissions per kilowatt-hour [59]. Emissions of NO_x can be below 25 ppm and CO emissions can be in the range of 10–50 ppm. Some emission control approaches, such as the diluent injection, lean premixed combustion, selective catalytic reduction, carbon monoxide oxidation catalysts, catalytic combustion and catalytic absorption systems, can also help to reduce NO_x emissions.

One typical application of gas turbine based cogeneration or trigeneration systems is for colleges or university campuses, where the produced steam is used to provide space heating in winter and cooling in summer. Another typical application is for the supermarket. In the U.S., CCHP systems have been widely installed in supermarkets to improve the system efficiency. Produced steam and heat from the gas turbine is used to drive the food-refrigeration system, which requires a huge amount of cooling energy, and to provide the basic space heating [60]. CCHP systems using gas turbines have attracted a certain amount of attentions. Exergy analyses for a combustion gas turbine based power generation system are addressed in [61], which can be used for engineering design and component selection. Investigations of CCHP systems using gas turbines can be found in [7,62]. In the latter one, a micro-CCHP system with a small gas engine and absorption chiller is built in Shanghai Jiao Tong University with the designed energy management method, which can also be used in large-scale CCHP systems whose overall efficiency can be as high as 76%.

2.3. Steam turbines

A steam turbine is a mechanical device that extracts thermal energy from pressurized steam, and converts it into rotary motion [63]. Compared with reciprocating steam engines, the higher efficiency and lower cost make steam turbines being used for about 100 years. The size of steam turbines can range from 50 kW to several hundred MWs for large utility power plants [64]. Because of the low partial load electric efficiency, steam turbines are not suitable for small-scale power plants. In the U.S. and some European countries, steam turbines have already been widely installed in large-scale CHP/CCHP systems. If given well maintenance, the life of the steam turbine can be extremely long, which can be counted in years.

The working principle of the steam turbine is different from those of reciprocating IC engines and combustion turbines. For the latter two, electricity is the product and the heat is generated as a by-product. However, for the steam turbine, electricity is the one generated as the by-product. When equipped with a boiler, the steam turbine can operate with various fuels including clean fuels, such as natural gas, and other fossil fuels. This character dramatically improves the flexibility of the steam turbine. In CHP/CCHP applications, the low pressure steam can be directly used for space heating or for driving thermally activated facilities.

GHG emissions of the steam turbine depend on the fuel it uses. If using some clean fuel, i.e., the natural gas, and adopting some effective emission control approaches, GHG emissions can be relative low. However, the low electric efficiency and long start-up time restrict the installation of steam turbines in small-scale CCHP systems and distributed energy applications [10]. Thus, steam turbines are only considered being utilized in large-scale industries.

2.4. Micro-turbines

Micro-turbines are extensions of combustion turbines. A micro-turbine manufactured by Capstone Turbine Corporation is shown in Fig. 2. The size of micro-turbines ranges from several kWs to hundreds kWs. They can operate on various fuels, e.g., natural gas, gasoline, diesel, etc. One important character of the micro-turbine is that it can provide an extremely high rotation speed, which can be used to efficiently drive the electricity generator. Because of the small size, micro-turbines are suitable for distributed energy systems, especially for CHP and CCHP systems. In the CCHP system, by-product heat of the micro-turbine is used to drive the sorption chillers and desiccant dehumidification equipment in summer, and to provide space heating in winter. The designed life of micro-turbines ranges from 40,000 to 80,000 h [65,66].

Fig. 2. Capstone C200 micro-turbine with power output of 190 kW.

Another key advantage of the micro-turbine is the low level of GHG emissions, thanks to the *gaseous fuels feature lean premixed combustor* technology. In addition, low inlet temperature and high fuel-to-air ratios also contribute to emissions of NO_x of less than 10 ppm. According to the data in [65], despite the stringent standard of less than 4–5 ppmvd of NO_x, almost all of the example commercial units have been certified to meet it.

Even though with the drawbacks of higher capital costs than reciprocating engines, low electrical efficiency, and sensitivity of efficiency to changes in ambient conditions, the compact size and low-weight per unit power, a smaller number of moving parts, lower noise, multi-fuel capability [67] and low GHG emissions still make the micro-turbine an arisen prime mover in distributed energy systems. Analyses of CHP/CCHP systems installing micro-gas turbines can be found in [68,67]. The latter one discusses the potential of using micro-turbines in CCHP systems in distributed power generation. If the high capital cost and low efficiency can be solved, the market potential could be increased dramatically.

In distributed energy systems, small-scale CCHP systems have been proven to be an efficient one. Due to the advantages, installing micro-turbine becomes the best choice for a small-scale CCHP system. Much work has been done to investigate the performance of using micro-turbines in CCHP systems. Tassou et al. [69] validate the feasibility of the application of a micro-turbine based trigeneration system in a supermarket. Beyond the feasibility, this paper also reveals that the economic viability of the system equipped with micro-turbines depends on the relative cost of natural gas and electricity. Karellas et al. [70] propose an innovative biomass process and use it to drive a micro-turbine and a fuel cell in a CHP system. The system efficiency can be extremely high when the gasification of biomass happens in high temperature. The innovative concept in this paper can be utilized in Biocellus. In 2002, the Oak Ridge National Laboratory (ORNL) presented their work of testing a micro-turbined CCHP system. The testing facility consists of a 30 kW micro-turbine for a distributed energy resource, whose exhaust is used to feed thermally activated facilities, including an indirect-fired desiccant dehumidifier and a 10-ton indirect-fired single-effect absorption chiller [71]. From the test data, the efficiency of the micro-turbine strongly depends on the output level and ambient temperature, which makes the full power output to be preferred. Bruno et al. [72] conduct a case study of a sewage treatment plant, which is a trigeneration system. The prime mover selected in this system is a biogas-fired micro-gas turbine. Hwang [73] in his work investigates potential energy benefits of a CCHP system with a micro-turbine installed. This paper gives the options to choose different types of chillers according to different configurations. Velumani et al. [74] propose and mathematically model a CCHP system with an integration of a solid oxide fuel cell (SOFC) and a micro-turbine installed. This plant uses natural gas as the primary fuel and the SOFC is fed with gas fuel. Other evaluations, analyses and control strategy designs for CCHP systems running with micro-turbines can be found in [75–79], to name a few.

2.5. Stirling engines

In contrast to the IC engine, the stirling engine is an external combustion engine, which is based on a closed cycle, where the working fluid is alternatively compressed in a cold cylinder volume and expanded in a hot cylinder volume [80]. Two basic categories of stirling engines exist: kinematic stirling engines and free-piston stirling engines. Also, the engine can fall into three configurations: alpha type, beta type and gamma type [81,82].

A stirling engine can operate on almost any fuel, e.g., gasoline, natural gas and solar energy. Compared to IC engines, stirling engines operate with a continuous and controlled combustion process, which results in lower GHG emissions and less pollution [83,82]. According to the data in [84], implementing the same capacity of 25 MW, NO_x emissions of the stirling engine is 0.63 kg/MWh, compared with 0.99 kg/MWh of the IC engine. It is worth mentioning that, since the working fluid is sealed inside the engine, there is no need to install valves or other mechanisms, which makes the stirling engine simpler than an IC engine. As a result, stirling engines can be relatively more safe and silent when running.

However, some challenges arise when using stirling engines in CHP/CCHP systems. The first one is the low specific power output compared with an IC engine of the same size. High capital cost is also a key factor that restricts its development. Another aspect is the working environment in CHP/CCHP systems. Unlike IC engines, the efficiency of a stirling engine drops when the working temperature increases. The last one but equally important is that the power output of the stirling engine is not easy to tune. Despite the above drawbacks, stirling engines have been put into some CHP/CCHP applications because of the flexibility in fuel source, long service time and low level of emissions. A small-scale CHP plant with a 35 kW hermetic four cylinder stirling engine for biomass fuels is designed, created and tested by the Technical University of Denmark, MAWERA Holzfeuerungsanlagen GesmbH and BIOS BIOENERGIESYSTEME GmbH in Austria [85]. Moreover, SIEMENS collaborated with some European boiler manufactures, such as Remeha and Baxi, to conduct a large field test in 2009 and market introduction in 2010 of micro-CHP systems with stirling engines.

The most promising aspect of the stirling engine must be that it can be solar driven. Because of the increasing rate of carbon tax and more attention paid on the GHG emissions, using of solar energy in CHP/CCHP systems gives more chances for the stirling engine.

Some theoretical work has also been done to investigate stirling engines installed in CCHP systems. Kong et al. [84] propose a trigeneration system with a stirling engine installed and claim that this system could save more than 33% primary energy compared to the conventional SP system. Aliabadi et al. [86] discuss the efficiency and GHG emissions of a stirling engine-based residential micro-CHP system fueled by diesel and biodiesel. According to the market assessment, stirling engines have not been widely applied in the CCHP market. To be further penetrated in CHP/CCHP systems, solutions to high capital cost, long warming up time and short durability of certain parts should be found [87].

Table 1
Comparisons among different prime movers.

Prime mover	Size (kW)	Pros.	Cons.	Emissions	Preferences and applications
IC engine	10–5000	• Low capital cost • Quick start • Good load following • High partial efficiency • High reliability	• Regular maintenance required	• High NO_x using diesel • Natural gas preferred	• Working with absorption/electric chiller • Small- to medium-scale
Combustion turbine	500–250,000	• High quality exhaust heat	• Unacceptable low partial efficiency	• NO_x 25 ppm • CO 10–50 ppm	• Applications with huge amount of thermal need Large-scale
Steam turbine	50–500,000	• Flexible fuel	• Low electric efficiency • Long start-up	• Depends on fuel	• Electricity as by-product, thermal need preferred • Large-scale
Micro-turbine	1–1000	• Flexible fuel • High rotation speed • Compact size • Less moving parts • Lower noise	• High capital cost • Low electric efficiency • Efficiency sensitive to ambient conditions	• NO_x < 10 ppm	• Distributed energy system • Micro- to small-scale
Stirling engine	Up to 100	• More safe and silent • Flexible fuel • Long service time • Can be solar driven	• High capital cost • Power output hard to tune	• Less than IC engine	• Solar driven • Small-scale
Fuel cell	0.5–1200	• Operate quietly • Higher reliability than IC and combustion engine • High efficiency	• Energy consumption and GHG emissions due to hydrogen producing	• Extremely low	• Micro- to medium-scale

2.6. Fuel cells

Another environment concerned type of prime mover is the fuel cell. Fuel cells convert chemical energy from a fuel into electricity through a chemical reaction with oxygen or other oxidizing agents, and produce water as a by-product [88–90]. Compared to other fossil fuel based prime movers, fuel cells use hydrogen and oxygen to generate electricity. Since water is the only byproduct, fuel cells are considered to be the cleanest method of electricity producing. Because of few moving parts contained, the fuel cell system has a higher reliability than the combustion turbine or the IC engine [91]. However, some drawbacks still exist to be the obstacles for the development and application of fuel cells. The production of the materials, i.e., oxygen, consumes energy and produces emissions. Several ways, e.g., electrolysis of water and generated from natural gas, exist to produce hydrogen for fuel cells, however, none of them can avoid both of high energy consumption and high emissions. In current market, there exists various types of fuel cells, i.e., proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and the previously mentioned SOFC.

In recent years, much work has been done to investigate fuel cells in CCHP systems. The most widely choice is the SOFC. Tse et al. [92] investigate a trigeneration system, which is jointly driven by a SOFC and a gas turbine, for marine applications. The efficiency of the configuration with double-effect absorption chiller can achieve 43.2% compared to 12% of the conventional system. In [93], Kazempoor et al. develop a detailed SOFC model, and study and optimize different SOFC system configurations. They also assess the performance of a building integrated with a trigeneration system, which comprises a SOFC and a thermally driven chiller. In [94], a SOFC with the capacity of 215 kW is combined with a recovery cycle for the sake of simultaneously meeting cooling load, domestic hot water demand and electric load of a hotel with 4600 m^2 area. An economic comparison between the trigeneration and SP systems indicates that, due to the lower heating value of the fuel, the maximum efficiency of 83% for energy trigeneration and heat recovery cycle can be achieved. Verda et al. [95] model a distributed power generation and a cogeneration system incorporated with the SOFC. The authors also compare three configurations for this system, based on different choices of refrigeration systems, i.e., single-effect absorption chiller, double-effect absorption chiller and vapor compression chiller, from both technical and economic points of view. Other work on the environmental, economical and energetic analyses of CCHP systems equipped with SOFCs can be found in [96–102], to name a few. In [103], the authors model the CCHP system with stationary fuel cell systems from thermodynamic and chemical engineering aspects; and optimize the operation for that. Margalef et al. [104] compare two strategies of operating a CCHP system equipped with a magnesium-air fuel cell (MAFC). The first strategy is to blend the exhaust gas with the ambient air; while the other one is to use the exhaust gas to drive an absorption chiller. The result shows that the second strategy is preferred, for the overall estimated efficiency is as high as 71.7%. Bizzarri [105] discusses the size effect of a PAFC system incorporated into a trigeneration system. Investigations reveal that the more the proper sizing is carried out for the highest environmental and energy benefits, the higher the financial returns will be. According to industry analysts Delta-ee, fuel cell CHO units have 64% of the CHP unit sale market, which doubles the results in 2011. It is becoming the most common technology employed in micro-CHP systems. In 2009, Tokyo Gas has its success in the first commercialized residential fuel cell CHP systems based on PEFC, i.e., ENE-FARM. In April, 2013, they released the new version that unit with lower cost, smaller size and lower CO_2 emission. This technology helps the fuel cell CHP take the market from other CHP prime movers. Ceramic Fuel Cell Limited's 1.5 kW SOFC CHP system, the so-called Blue Gen targets the market of social housing, shared accommodation,

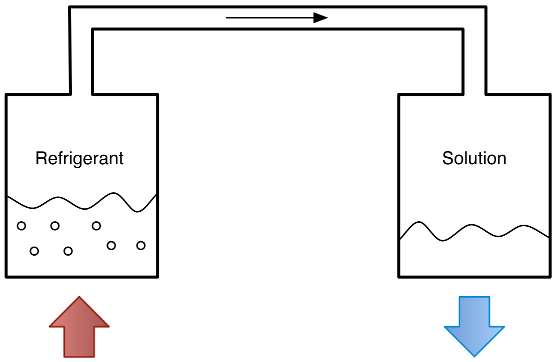

Fig. 3. Absorption process.

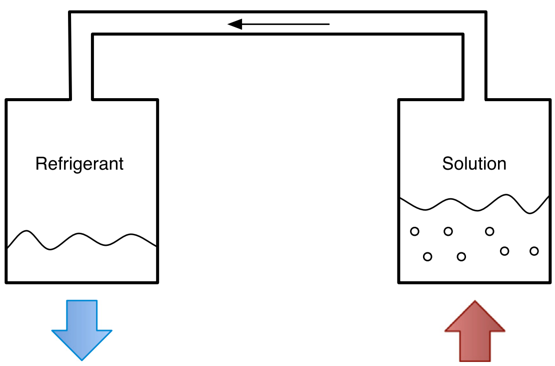

Fig. 4. Separation process.

school and small business. This system can be beneficial for academic use, for every data in this system can pulled out for analyzing. While, nowadays, feed-in tariffs and financial support are still the obstacle for the development of this type of CHP system. California's Self Generation Incentive Program is a good example for all the policy makers.

The comparisons among different prime movers can be found in Table 1.

3. Thermally activated technologies

The most efficient solution to provide cooling is to utilize the rejected heat instead of electricity. This solution is realized by the thermally activated technology, which is dominated by the sorption cooling. The difference between the sorption cooling and the conventional refrigeration is that the former one uses the absorption and adsorption processes to generate thermal compression rather than the mechanical compression. One important reason for the CCHP system being efficient and of low GHG emissions is because space cooling and heating can be provided by using the rejected heat from the prime mover along with the electricity generating. This cascade utilization of heat owes to the thermally activated technology. In conventional SP systems, approximately two-thirds of the fuel used to generate electricity is wasted in the form of rejected heat. By introducing thermally activated technologies, the electric load for cooling is shifted to the thermal load, which can be fully or partially achieved by absorbing or adsorbing the discard heat from the prime mover. The main application of the sorption refrigeration is for CCHP systems in residential buildings, hospitals, supermarkets, office buildings and district cooling systems [106].

Mainly, three types of the thermally activated technologies exist, i.e., absorption chiller, adsorption chiller and desiccant dehumidifier. Since the temperature of the discard heat from prime movers can lie in different ranges, thermally activated facilities should be chosen to couple with prime movers. For example, if the heat source temperature is around 540 °C, then the suitable choice is a double-effect/triple-effect absorption chiller.

3.1. Absorption chillers

Investigations of the absorption cycle began in 1700s when it was found that ice could be produced by an evaporation of pure water from a vessel contained within an evacuated container in the presence of sulfuric acid [107]. The absorption chiller is one of the most commonly used and commercialized thermally activated technologies in CCHP systems. The difference between an absorption chiller and a vapor compression chiller is the process of compression. Since absorption chillers use heat to compress the refringent vapor instead of mechanically using rotating devices, they can be driven by the steam, hot water or high temperature exhaust gas. As a result, electricity needed for the conventional refrigeration can be dramatically reduced, and the noise of the cooling process can be lowered significantly.

The working process of an absorption chiller can be divided into two processes: The absorption process and the separation process. The absorption process can be shown in Fig. 3. The left vessel contains the refrigerant and the right vessel is filled with a mixture of refrigerant and adsorbent. Caused by the absorption process of the refrigerant vapor in the right vessel, pressure and temperature in the left vessel will drop. The temperature reduction in the left vessel is the refrigeration process. At the same time, as a result of the absorption process in the right vessel, heat must be rejected to the surroundings.

As the absorption process continuing, the solution in the right vessel gradually becoming saturated. To keep the capability of absorbing, refrigerant must be separated from the solution. Fig. 4 shows the separation process, which can be regarded as a reverse of the absorption process. Heat from the heat source is used to dry the refringent from the saturated or almost saturated solution. The refrigerant vapor is then condensed by a heat exchanger to act in the next cycle of absorption process.

Chemical and thermodynamic properties of the working fluid determine the performance of an absorption chiller. The working fluid should be chemically stable, non-toxic and non-explosive. Moreover, in liquid phase, it must has a margin of miscibility within the operating temperature range of the cycle [108]. According to [109], there are around 40 refrigerant compounds and 200 absorbent compounds available for the absorption chiller working fluid. However, the most commonly used two are the lithium-bromide/water (liBr/water) and the ammonia/water (NH_3/water). Usually, LiBr/water absorption chiller is used in air cooling applications with evaporation temperature in the range of 5–10 °C; while NH_3/water absorption chillers are used in small-scale air conditioning and large industrial applications with evaporation temperature below 0 °C [106].

In the literature, absorption chillers have been widely installed in CCHP systems. In 2002, the U.S. government awarded Burns & McDonnell Engineering Co. a development contract of building an integrated gas turbine energy system based on improved CHP/CCHP technology. This plant is powered by a 4.6 MW Solar Turbines Centaur 50 gas turbine and two-stage indirect fired Broad Co. absorption chillers [110]. A small-scale CCHP system, installing a micro-turbine and an absorption chiller is demonstrated in the University of Maryland [111]. By adding the absorption chiller in the decentralized SOFC based CCHP system, with the cost of increase of about 0.7% compared to conventional systems, the CO_2 emissions can be reduced by 30%. In [102], a decentralized system with the integration of an SOFC and a double-effect

LiBr/water absorption chiller is investigated. In [112], the authors introduce a CCHP system, with three engines and a total electrical power production of 9 MW, which supplies the thermal energy to drive an NH_3/water absorption chiller ARP-M10 by Colibri. This configuration is applied in a margarine factory in Netherlands, a vegetable freezing factory in Spain, and a dairy factory in Spain. All of the three applications show the cost reduction by using this system.

3.2. Adsorption chillers

The development of the adsorption cooling began when the phenomenon of adsorption refrigeration caused by ammonia adsorption on AgCl was discovered by Faraday in 1848 [113]. Similar as absorption chillers, adsorption chillers make use of the discard heat from the prime mover to provide space air conditioning. One important difference of an adsorption chiller from an absorption chiller is that the former one can be driven by low temperature heat source. Furthermore, the noiselessness, solution pump free, corrosion and crystallization trouble free, and small volume make adsorption chillers suitable for CCHP systems, especially small-scale ones [114–116].

Different from the absorption chiller, in which a fluid permeates or is dissolved by a liquid or solid, the adsorption chiller provides cooling by using solid adsorbent beds to adsorb and desorb a refrigerant. Similar to the two processes in the absorption chiller, temperature of the adsorbent changes according to the refrigerant vapor adsorbed and desorbed by adsorbent beds. A simple adsorption refrigeration circuit consists of a solid adsorbent bed, a condenser, an expansion valve and an evaporator [34]. The refrigeration process of the adsorption chiller can also be divided into two processes, i.e., absorbent heating and desorption process and the adsorption process. In the first process, the adsorbent bed is connected with a condenser first. Driven by a low temperature heat source, the refrigerant is condensed in the condenser and heat is released to the surroundings. Following that, in the adsorption process, the adsorbent bed is connected to an evaporator, at the same time disconnected from the condenser. Then cooling is generated from evaporation and absorption processes of the refrigerant. However, this simple adsorption chiller provides cooling in an intermittent way. To continuously provide cooling, two absorbent beds should be installed in the system together, in which one bed is heated during the desorption process and the other one is cooled during the adsorption process.

The same as absorption chillers, adsorption chillers have no internal mechanical moving parts either. As a result, they can not only run quietly, but also need no lubrication and less maintenance. In addition, adsorption chillers are always made modularity, which makes them suitable for the cooling capacity expansion. Moreover, as mentioned before, since no electricity and fuel is needed to drive the chiller, low level of GHG emissions is guaranteed. Because of the advantages of the adsorption chiller, research and demonstrations of this type of chiller installed in the CCHP system have been developed widely. Li et al. [117] discuss the performance of a silica gel–water adsorption chiller in a micro-CCHP system according to different working conditions, especially for different electric loads. In 2000, a CCHP system, equipped with a fuel cell, a solar collector and an integration of a mechanical compression chiller and an adsorption chiller, was installed in the St. Johannes Hospital [10]. In the same year, a CCHP system with an adsorption chiller began to operate in the Malteser's Hospital, Germany. Shanghai Jiaotong University (SJTU) has been investigating the applications of adsorption chillers in CCHP systems for many years. In 2004, SJTU set up a gas-fired micro-CCHP system consisting of a small-scale power generator set and a novel silica gel–water adsorption chiller [106].

3.3. Desiccant dehumidifier

A desiccant dehumidifier removes the humidity from the air by using materials that attract and hold moisture. To achieve comfort cooling, sensible cooling, aiming to lower the air temperature, and latent cooling, which means reducing humidity, should be achieved simultaneously. Since, by introducing desiccant dehumidifiers, the control of humidity independent of the temperature is allowed; potentially wasted thermal energy can be used to reduce the latent cooling load; and bacteria and virus can be scrubbed out, desiccant dehumidifiers always operate with chillers or conventional air-conditioning systems to provide comfort cooling and to increase overall system efficiency [10,118].

Mainly, there exist two commercialized types of desiccant dehumidifiers, which are distinguished by desiccant types, i.e., solid desiccant dehumidifier and liquid desiccant dehumidifier. Solid desiccant dehumidifiers are usually used for dehumidifying air for commercial HVAC systems; while liquid desiccant dehumidifiers are popular in industrial or residential applications. Desiccant dehumidifiers are suitable for CHP/CCHP systems, because the regeneration process in the desiccant system provides an excellent use of waste heat [119]. In [120], the authors introduce a CCHP

Table 2
Comparisons among different thermally activated technologies.

Thermally activated technology	Size (chilling power)	Pros.	Cons.	COP	Preference
Absorption chiller	10 kW–1 MW	• Driven by steam • Low noise • Can be driven by low quality heat source • Low GHG emission	• Less efficient than compressor-drive chiller	Up to 1.2	• LiBr/water: evaporation temperature 5–10 °C • NH_3/water: evaporation temperature <0 °C • Small- to Large-scale • Double-effect preferred
Adsorption chiller	5.5–500 kW	• Driven by steam • Small size • Noise free • Corrosion and crystallization trouble free • No lubrication • Low GHG emissions	• Can only be driven by high quality heat • High capital cost	0.6	• Small-scale
Desiccant dehumidifier	N/A	• Control of humidity independent of the temperature is allowed • Reduce the mechanical cooling load	• High capital cost • Regular maintenance required	N/A	• Solid: HVAC systems • Liquid: industrial and residential applications

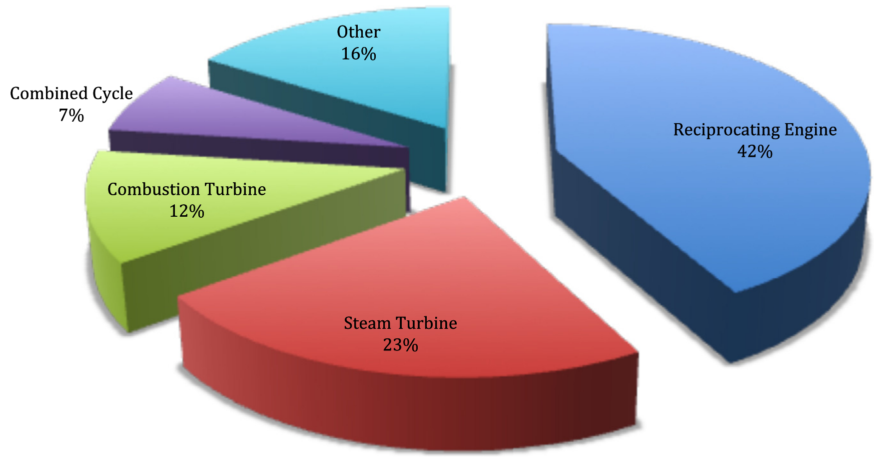

Fig. 5. Existing CHP/CCHP sites classified by prime movers.

system utilizing the solid desiccant cooling technology. Researchers in Tsinghua University, China, also carry out a laboratory research to assess the operational performance and energy efficiency of a CCHP system installing a liquid desiccant dehumidifier [121]. The data collected from summer and winter show that the only way to increase the overall efficiency is to install more waste heat driven equipment to utilize the low quality waste heat. In [52], the authors assess a desiccant dehumidifier system in a CHP application incorporating an IC engine. Badami et al. [122] analyze the performance of a trigeneration plant with liquid desiccant cooling system installed at the Politecnico di Torino, Italy. In this paper, the authors provide both of the energetic and economic analyses to show the huge potential of using this type of trigeneration system. The desiccant dehumidifier system allows that the temperature and humidity in the classroom can be controlled. The air conditioning service can also make this system be suitable for academic use. It is proved that with the liquid desiccant cooling system, we can make full use of the waste heat to provide cooling service in the summer and the overall efficiency can be dramatically increased.

The comparisons among different thermally activated technologies can be found in Table 2.

4. System configuration

An economical, efficient and of low emissions CCHP system should be designed with fully consideration of energy demands in a specific area, prime mover and other facilities' types and capacities, power flow and operation strategy, and the level of GHG emissions. The selection of facility types belongs to the design of the system configuration, which emphasizes on the selection of prime movers according to current available technologies, and on the system scale. It is well known that different climate conditions in different areas lead to different patterns of energy demands. For example, in conventional CHP systems, steam turbine based plants are always used as heat plants with electricity generated as a by-product in some cold areas. While in the temperate zone, in summer, electricity needed by the air conditioning could be of huge amount. Thus, in this kind of area, combustion turbine based CHP systems are popular. Some CHP/CCHP applications based on prime mover selections have been mentioned in Section 2. The existing CHP/CCHP sites in the market sorted by prime movers can be shown in Fig. 5. With a selected CCHP system configuration, operation strategy is the key to achieve the most efficient way for the CCHP to operate. The operation strategy determines how much electricity or fuel should be input to the system according to the demands; which facility should be shut down to keep the whole system efficient; how the energy carriers flow between facilities; and how much is the power one facility should operate at. With a designated configuration and an appropriate operation strategy, suitable sizing and optimization can make the system operate in an optimal way. Here, CCHP applications categorized by the plant size will be mainly discussed.

Categorized by the rated electricity generation capacity, the CCHP system can land in micro-scale (under 20 kW), small-scale (20 kW–1 MW), medium-scale (1 MW–10 MW) and large-scale (above 10 MW).

4.1. Micro-scale CCHP systems

Micro-scale CCHP systems are the ones with rated size under 20 kW. Recently, much work has been done to investigate and analyze micro-scale CCHP systems, for they are suitable for distributed energy systems. In the literature, Easow et al. [123] discuss the potential of the micro-trigeneration system being applied in the decentralized cooling, heating and power. By testing an experimental plant, which is a micro-trigeneration system with a liquefied petroleum gas driven Bajaj 4-stroke IC engine, the increased energy supply reliability and security, lower energy cost, higher efficiency and less fuel energy loss are verified in this paper. In North Carolina Solar Center, Raleigh, North Carolina, 2010, an integrated micro-CCHP and solar system was installed to demonstrate technical and economic feasibility of incorporating photovoltaic (PV), solar thermal, and propane-fired CHP systems into an integrated distributed generation system [124]. The rated output of the CHP plant incorporated, PV, and solar thermal is 4.7 kW plus 13.8 kW, 5.4 kW, and 4.1 kW, respectively. Thermal energy produced by this system can be used for space heating, domestic hot water, process heating, dehumidification and absorption cooling. With this solar based CCHP system, CO and NO_x emissions can be reduced to below 250 ppm and below 30 ppm, respectively. Other experimental and test results of micro-CCHP systems can be found in [125–127], to name a few. In addition, various work on energetic, economic and thermodynamic analyses has been done in recent years. In the most recent work, in [128], the authors provide an analysis of matching prime mover heat sources to thermally driven devices in a micro-scale trigeneration system. The T-Q analysis of the prime mover waste heat in this literature also indicates the promise of incorporating micro-turbines, SOFCs and HT-PEMFCs into the trigeneration system. Other analyses can be referred to [129–134]. Some researchers also focus on the optimization of micro-CCHP systems. Arosio et al. [135] model a

micro-scale CCHP system based on the linear optimization and incorporate the Italian tariff policy into this model. The proposed model allows to evaluate the influence of each parameter on the system performance. Other optimization research can be found in [136,127]. Recently, some renewable energy, such as the solar energy, has been implemented in the CCHP system to further reduce GHG emissions. In [137], a micro-trigeneration system equipped with a solar system is studied. This system is integrated by a micro-turbine with output power of 5 kW and a LiBr/water absorption chiller. The heat source for the absorption chiller and the micro-CHP system is a solar storage tank. Installing the solar system can efficiently increase the overall efficiency and consume less primary energy. Immovilli et al. [138] compare a conventional CCHP system with the one based on solar energy. The configuration of a PV collector coupled with a vapor compression cooling system is verified to be the best commercially available solution. Besides the PV, they also propose two technical solutions for the solar CCHP to access residential applications, i.e., concentrated sunlight all-thermoacoustic and hybrid thermo-PV systems. Beyond the above, some novel micro-scale CCHP structures are also proposed. Henning et al. [120] investigate a micro-trigeneration system, whose air conditioning facilities integrate a vapor compression chiller and a desiccant wheel, for the indoor air conditioning in mediterranean climate. The research results show that, compared to conventional technologies, an electricity saving of 30% can be achieved. In [139], the authors investigate the performance of an absorption chiller, which is installed in a micro-scale BCHP system, under varying heating conditions. Huangfu et al. [5] introduce a novel micro-scale CCHP system which can be applied in domestic and light commercial applications. Evaluations and analyses in this literature show that this micro-CCHP system enjoys good economic efficiency with a payback period of 2.97 years, which is quite short; also the electric load conditions determine the electric efficiency, which means that, compared to half load, the system can perform better when operating at full load.

4.2. Small-scale CCHP systems

Small-scale CCHP systems are the ones with rated size ranging between 20 kW and 1 MW. They have been widely used in the supermarkets, retail stores, hospitals, office buildings and university campuses. Different types of prime movers and refrigeration systems can be combined freely according to energy demands. Around the world, small-scale CCHP plants have been installed in many applications. A 500 kW biomass CCHP plant is installed in the Cooley Dickinson Hospital, Northampton, Massachusetts, which is a 55,742 m^2 hospital with 140 beds [140]. In 1984, the first boiler installed in this system was a Zurn-550 HP biomass boiler, which was fired by virgin wood chips. Then in 2006 and 2009, due to increased energy demands, an AFS-600 HP water/fire tube high pressure boiler, two 250 kW Carrier Energent micro-steam turbines and a 2391 kW absorption chiller were installed consecutively. This CCHP system has brought a lot of benefits to this hospital, especially the 99.5% particulate removal accomplished by the Multiclone separator and Baghouse. The East Bay Municipal Utility District (EBMUD), which was a publicly owned utility that provided water service to portions of two countries in the San Francisco bay area, began to use a 600 kW micro-turbine CHP/chiller system at its downtown Oakland administration building in 2003 [141]. This system is composed by ten 60 kW Capstone micro-turbines and one 633 kW YORK absorption chiller. The total project costs $2,510,000, whose payback period is estimated to be 6–8 years. Another small-scale CCHP application is in the Smithfield Gardens, which is a 56-unit affordable assisted-living facility in Seymour, Connecticut [142]. This system includes a 75 kW Aegen 75LE CHP module, an American Yazaki absorption chiller, and a Baltimore Air Coil cooling tower. With this system installed, the Smithfield Gardens can save 22% on its annual energy costs. With the pollution controlled by the Non-Selective 3-way Catalytic Reduction System, CO_2 and NO_x reductions can achieve 32% and 74%, respectively. Vineyard 29, a winery located in St. Helena, California, installs a 120 kW micro-turbine/chiller system to reduce GHG emissions as well as toxins into the environment [143]. Two 60 kW Capstone C60 micro-turbine systems are installed to provide electricity and thermal energy. This is a good example of waste heat cascade utilization. Through the heat recovery system, hot water produced is for the wine processing, and the other part of thermal energy is adsorbed by a 70 kW Nishiyodo adsorption chiller to provide space cooling. In addition, a Dolphine pulsed power system is used in the EvapCo cooling tower. With a total capital cost of $210,000, the estimated payback period is 6–8 years, which means $25,000–$38,000 per year. In [144], the authors provide experimental results for a real small-scale CCHP system operating at full load and partial load. This test plant, consisting of a 100 kW natural gas-powered micro-turbine and a liquid desiccant system, is installed at the Politecnico di Torino, Turin, Italy. Comparisons of primary energy savings (PESs) among different prime mover load situations are made. The data shows that adopting the partial load strategy can cause an energetic performance decrease. Katsigiannis et al. [145] conduct two case studies in the indoor Swimming Pool Building, and the Law School Building in the Democritos University of Thrace, Greece, to investigate their systematic computational procedure for assessing a small-scale trigeneration system. The procedure includes an indirect estimation of pertinent loads, indoor swimming pool heating, CCHP facility selection, system sizing and economic evaluation. This work further verifies that the system performance mainly depends on the system size. Less cost and pollution can be readily observed from the simulation. Other applications and test work can be found in [146–148].

In the theoretical work, Chicco et al. [149] summarize some key issues and challenges of the planning and design problems for a small-scale trigeneration system. Time domain simulations are conducted to assess each energy vector production within the system by introducing new performance indicators, i.e., trigeneration primary energy saving (TPES), electrical-side incremental trigeneration heat rate (EITHR), thermal-side incremental trigeneration heat rate (TITHR) and cooling-side incremental trigeneration heat rate (CITHR). Other energetic, economic and thermodynamic analyses can be referred to [122,150,151]. In [122], the authors investigate an innovative natural gas based CCHP system, whose electricity, heating and cooling capacities are 126 kW, 220 kW and 210 kW, respectively. The gas-fired IC engine works in pairs with a liquid LiCl/water desiccant cooling system. The authors also give energetic and economic analyses, including the influence of the fuel and electric price can make, and indices variations due to the plant cost, of this system. The proposed system has a payback period of around 7 years, and will provide €200,000–220,000 net present value after 15 years.

Some researchers focus on optimization problems involved in the small-scale CCHP system design. Abdollahi et al. [152] propose a multi-objective optimization method for a small-scale distributed CCHP system design. The environmental impact objective function is defined to be the cost. An economic analysis is conducted using the total revenue requirement (TRR) method. They adopt the genetic algorithm (GA) to find a set of Pareto optimal solutions; and apply the risk analysis to complete the decision-making to find the optimal solution from the obtained set. In [153], an optimization problem of the energy management in the CCHP system is solved by the mixed integer linear programming (MILP). The solution aims to control the on/off

status of system components. A comparison, whose data is collected from a 985 kW plant, is made between the proposed energy management and conventional management. The proposed optimal strategy allows a one year reduction of the payback period. Hossain et al. [154] present a design and a construction of a novel small-scale trigeneration system driven by neat non-edible plant oils, including jatropha, jojoba oil, etc. The use of local available non-edible oil can leave this plant run without depending on imported petroleum fuel, which results in a high economical efficiency. Moreover, GHG emissions can be dramatically reduced by using the rejected heat from the prime mover to provide cooling and heating.

4.3. Medium-scale CCHP systems

As mentioned, medium-scale CCHP systems are those with rated power ranges of 1 MW–10 MW. From this level of rated size, CCHP systems begin to operate in large factories, hospitals, schools, etc. A 4.3 MW CCHP plant has been severing the Elgin Community College, Elgin, Illinois, since 1997 [155]. The first phase of this plant, which was a 3.2 MW CCHP plant, was installed in 1997 to provide electricity, low pressure steam and absorption cooling to main campus buildings. In 2005, due to the campus expansion, the generation set and the absorption chiller were both expanded in the second phase. The prime mover in this system is a combination of four 800 kW Waukesha reciprocating engines and one 900 kW Waukesha reciprocating engine. Cooling is provided by one YORK 1934 kW absorption chiller and one Trane 2813 kW absorption chiller. The heat recovery equipment includes five Beaird heat recovery silencers and five Beaird exhaust silencers. The two phases cost $2,500,000 and $1,200,000, respectively. The payback period for the second phase is about 4 years with annual savings around $300,000. Another medium-scale CCHP application is the one with a capacity of 3.2 MW installed in Mountain Home VA Medical Center, Mountain Home, Tennessee, in 2011 [156]. This medical center serves for 170,000 military veterans in surrounding countries. The whole plant consists of one 3.2 MW dual-fuel engine generator set, fired by landfill bio-gas, two 1.8 MW back up diesel-fired engine generator sets, a heat recovery steam generator, and a 3.5 MW absorption chiller. With this plant, the estimated cost savings over 35 years can be $5–15 million. In the University of Florida, a 4.3 MW CHP plant began to serve the Shands HealthCare Cancer Hospital since 2008 in order to solve the problem of increasing electricity and fuel prices, to reduce budget, and to reduce GHG emissions. The total installation costs $45 million. This system, designed by Gainsville Regional Utilities (GRU), consists of one 4.3 MW combustion turbine, one 6.5 t/h heat recovery steam generator, one 4.2 MW steam turbine centrifugal chiller, two 5.3 MW electric centrifugal chillers and one 13.6 t/h packaged boiler. The 4.3 MW natural gas turbine provides 100% of the hospital's electric and thermal needs. By using this system, a total thermal efficiency of 75% can be achieved. Other applications of medium-scale CCHP systems can be found in [157–159], to name a few.

Moreover, researchers also concern on the theoretical research on medium-scale CHP/CCHP systems. In [160], in order to raise the energy efficiency, the authors propose a trigeneration scheme for a natural gas processing plant by installing a turbine exhaust gas waste heat utilization. This trigeneration system makes use of the rejected heat from the gas turbine to generate process steam in a waste heat recovery steam generator. A double-effect LiBr/water absorption chiller is driven by the process steam to provide space cooling; while another part of the process steam is used to meet furnace heating load and to supply plant electricity in a combined regenerative Rankine cycle. The measured CCHP power output is 7.9 MW. The expected annual operating cost savings can achieve as high as 20.9 million dollars with only one year payback period. In [161], the authors design a CCHP system for a business building in Madrid, Spain. Basic demands of this building are 1.7 MW of electricity, 1.3 MW of heating and 2 MW of cooling. By designing the operation strategy and optimizing facility capacities, the final design of the configuration is given to be an integration of three 730 kW IC engines, one 3 MW double-effect absorption chiller, one conventional chiller of 4 MW, and one 200 kW boilers for back up. Because of the incorporating of a thermal solar plant, the capital cost is 3.32 M€, which is expected to be paid back in 11.6 years. Compared to conventional trigeneration systems, PESs in this plant increase a lot due to the incorporation of the thermal solar plant into the trigeneration plant. In [162,163], the authors propose a methodology for thermodynamic and thermoeconomic analyses of a trigeneration system equipped with a Wartsila 18V32GD model 6.5 MW gas-diesel engine. This system is installed in the Eskisehir Industry Estate Zone, Turkey. Efficiencies of energy, exergy, Public Utility Regulatory Policies Act and equivalent electrical of the trigeneration system are determined to be 58.94%, 36.13%, 45.7% and 48.53%. This CCHP system can also be transplanted to an airport to provide cooling, heating and electricity. Other theoretical work can be referred to [164,165].

4.4. Large-scale CCHP systems

Large-scale CCHP systems are categorized to be the ones with output power of above 10 MW. This type of CCHP system can provide substantial electricity for industry use, and vast heating and cooling for universities and residential districts, which with a high density of people. So far, as the problem of GHG emissions and increased price of electricity and fuel, an increasing number of large-scale CCHP systems have been installed to serve. The University of Michigan, Ann Arbor, Michigan, began to adopt the cogeneration system in 1914 [166]. Combined with absorption chillers, this 45.2 MW CHP plant consists of six conventional gas-/oil-fired boilers from Combustion Engineering, Wickes, Murray and Foster Wheeler (in total of 453.6 t/h of steam capacity); three Worthington back-pressure/extraction steam turbine generators (rated at 12.5 MW each); two gas/oil solar combustion turbines (3.7 and 4 MW, respectively); and two Zurn heat recovery steam generators (HRSG) with supplemental gas firing (29.5 t/h each). The electricity production of this plant can rarely reach the maximum capacity, for the plant has to provide steam for other use, such as, in summer, the absorption chiller. The system installed saved the university $5.3 million in 2004. In San Diego, California, the University of California at San Diego installed a 30 MW polygeneration plant in 2001 [167]. The 30 MW combined cycle is composed by two 13.5 MW Solar Turbines Titan 130 gas turbine gen-sets and a 3 MW Dresser-Rand steam turbine. The rejected heat is used to run a steam driven centrifugal chiller; to provide domestic hot water for campus use; and to run the steam turbine for additional electricity production. The whole system can achieve 70% gross thermal efficiency. Annually, by installing this set of system, $8–10 million can be saved. In this site, an emission control system, i.e., SoLoNOx™, is adopted to control the level of NO_x emissions to 1.2 ppm, which is much lower than the permitted 2.5 ppm. Another classic large-scale CCHP application is the plant installed in the University of Illinois at Chicago [168]. This plant, established from 1993 to 2002, is separated into two parts: the east campus system and the west campus system. In the east campus CCHP plant, two 6.3 MW Cooper-Bessemer dual-fuel reciprocating engine generators and two 3.8 MW gas reciprocating engine generators are installed as the prime mover. Cooling is provided by one 3.5 MW Trane two-stage absorption chiller, two 7 MW YORK electrical centrifugal chillers and several remote building absorption chillers. The capital cost of $25.7 million is

Table 3
Comparisons among different system configurations.

Configuration	Size	Preference
Micro-scale	< 20 kW	• Distributed energy system
Small-scale	20 kW–1 MW	• Supermarkets, retail stores, hospitals, office buildings, and university campuses
Medium-scale	1 MW–10 MW	• Large factories, hospitals, and schools
Large-scale	> 10 MW	• Large industries • Waste heat can be used for universities and district with a high density of people

estimated to be paid back in 10 years. PESs, CO_2 reductions, NO_x reductions and SO_2 reductions can achieve 14.2%, 28.5%, 52.8% and 89.1%, respectively. In the west campus, because of the large energy demand in the hospital and several buildings, an additional 37.2 MW generation set, composed by three 5.4 MW Wärtsilä gas engines and three 7 MW Solar Taurus turbines, is added. Besides the prime mover, an additional 7 MW absorption chiller is also installed in the west campus CCHP plant. With the capital cost of $36 million, the payback period is estimated to be 5.1 years. Other applications that show the success of using CCHP scheme in large-scale systems can be found in [169–171].

The comparisons among different system configurations can be found in Table 3.

5. System management, optimization and sizing

Once the configuration of a CCHP system is determined for a specific application, the next step is to manage the energy flow reasonably and to select an appropriate facility capacity to achieve maximum cost and emission reduction. Actually, in some recent system optimization work, the operation strategy, power flow and facility size are optimized simultaneously. In this section, some conventional and novel operation strategies, system optimization approaches and sizing work will be introduced.

5.1. Conventional operation strategies

Two classical operation strategies for the CHP/CCHP systems are FEL and FTL [172,173], which can also be referred to as the electric demand management (EDM) and the thermal demand management (TDM) [174]. In the FEL strategy, the CCHP system firstly purchases the fuel to provide enough electricity for the building users. If the excess heat cannot meet the cooling and heating demand, additional fuel should be purchased to feed the auxiliary boiler to generate enough thermal energy. In the FTL strategy, the CCHP system firstly meets the thermal demand, including the cooling and heating, then if the electricity provided by the PGU cannot meet the building users' demand, additional electricity should be purchased from the local grid to compensate for the gap. However, both of the FEL and FTL strategies can inherently waste a certain amount of energy. This is because, for instance, when the CCHP system runs under the FEL strategy to provide enough electricity for the building users, if the thermal demand is less than the thermal energy PGU provides, the excess thermal energy will be wasted. It is a similar case for the FTL strategy. The comparisons and analyses of the two strategies are investigated in [33,174–180], to name a few.

5.2. Novel operation strategies

In order to reduce the energy waste and to reduce primary energy consumptions, annual total cost and GHG emissions, it is necessary to design an optimal operation strategy. Due to different definitions of “optimal”, the operation strategies designed are different. In [181], Liu et al. proposed a novel operation strategy for the CCHP system by using the concept of “balance”. By adjusting the electric cooling to cool load ratio between the electric chiller and absorption chiller, the balance point of users electric demands, cooling demands and heating demands evolves to be a balance space. Optimal operation strategy is designed to keep the energy balance. The case study shows that, running under the proposed operation strategy, the primary energy consumption (PEC), carbon dioxide emission (CDE), and the annual total cost (ATC) are much lower than those of the SP system. In [182], the author proposes an optimal operation strategy for an offline nonlinear model, i.e., TOOCS-off, of a CCHP system. This optimization model considers the electric and thermal load in each time interval, prices of electricity sold to costumers or purchased from utility, and prices of heating and cooling. In the cost function of the TOOCS-off model, the total economic benefit of this system is maximized during total daily operation time. In the constraints, facilities' thresholds and output upper bounds are considered simultaneously. An CCHP system with a capacity of 143 kW, equipped with a 450 kW auxiliary boiler, a 600 kW absorption chiller and a 800 kWh content heat storage tank, is used to verify the feasibility of this offline model and the optimal operation strategy. Based on source PEC, Fumo et al. [183] analyze four CCHP system operation conditions, including power and cooling without requiring boiler operation (in spring/fall), power and cooling requiring boiler operation (in summer), power and heating without requiring boiler operation (in spring/fall) and power and heating requiring boiler operation (in winter). The results of this study can contribute to the design of the operation strategy to reduce undesired increase of energy consumptions. In [175], the authors design an optimal operation scheme for a CCHP system by considering the PEC and emissions of pollutants besides the energy cost. The operation is optimized by an optimal energy dispatch algorithm. The evaluation of the performance of a CCHP system, operating under the propose strategy, is conducted using five cities' realistic climate data. Cardona et al. [184] proposed a profit-oriented optimal operation strategy, considering both of the articulated energy tariff system and the technical characteristics of components. In [185], instead of the profit-oriented strategy and the primary energy-oriented strategy, the authors adopt an emission-oriented strategy in order to reduce GHG emissions. The control scheme in the proposed strategy is an on–off control, i.e., if the level of GHG emissions is greater than a specific value, then the PGU should stop; otherwise, the PGU runs to meet the energy demand. A comparison of GHG emissions of the proposed strategy, profit-oriented strategy and primary energy-oriented strategy is made to show the effectiveness of the proposed operation strategy. In [186], the authors propose an FEL/FTL switching operation strategy for the CCHP system. An integrated performance criterion, including PEC, CDE and cost (COST), is used to determine the switching action between FEL and FTL strategies. However, the inherent energy waste still exists. In [187], by considering the uncertainties of the price of the purchased electricity, the delivered demand for electricity, and the marginal cost of self generation, the authors propose an operation strategy design method using a risk management approach. By using the risk metrics, the steam and gas turbine generated electric power, the benefits and costs can be forecasted. Moreover, an optimal control tool, i.e., the model predictive control (MPC), is also used in [187] to schedule the operation strategy. Mago et al. [172] propose an optimized operation strategy, which can be referred to as following the hybrid electric-thermal load (HETS). The analyses and evaluations show that, when operating under the HETS, a CCHP system can perform better in the aspects of PEC, operational

cost and CDE, when compared to FEL and FTL strategies. In [188], the optimization of the operation strategy is formulated to be a linear programming (LP) problem with the objective function set to be the operation variable cost. This problem is constrained by capacity limits, equipment efficiencies, energy balance equations and demand constraints. The obtained optimal operation strategy is classified in nine operational modes due to the price of electricity from grid, electricity sold back price, auxiliary heat and waste heat. A thermoeconomic analysis, based on the marginal cost, is also conducted to investigate the relationship between the optimal operation mode and energy demands, as well as the prices of consumed resources. Aiming to maintain the system autonomy to ensure the grid reliability and to minimize excess power production, Nosrat et al. [189] propose a dispatch strategy for a PV-CCHP system, in which the thermal energy waste can be significantly reduced. Decision-making of this dispatch strategy depends on the output of the PV array and is separated into four steps. In each step, several operation conditions are analyzed to choose the strategy between FEL and FTL. The results show that an improvement of 50% can be achieved by using this dispatch strategy. Because the strategy is chosen from FEL and FTL directly, the inherent energy waste still cannot be avoided.

5.3. System optimization

To optimize the system performance, a mathematical model should be constructed first to make use of the various optimization algorithms. In the literature, much work on the optimization has been done to investigate the CCHP optimization problem. Among these approaches, due to the on–off character of the components, mixed integer programming is the most widely used one. Based on the concept of *superstructure*, the authors in [190] propose a systematic method to optimize the size of a CCHP system powered by natural gas, solar energy and gasified biomass. Modelled by the mixed integer nonlinear programming (MINLP) model, PESs, GHG emissions and economic feasibility are optimized. They also point out that the trade-off between the economical and environmental concerns should be taken into consideration when designing a CCHP system. Following the previous work, which only concerns the monthly average requirement, Rubio et al. [191] take the hourly data, analysis and energy storage system into consideration. This NP problem is solved by a generalized reduced gradient (GRG)-based algorithm. In [192], Buoro et al. model a trigeneration system to be an MINLP model. They propose a scheme of several buildings connected with each other. Thus, the optimal solution of this problem contains prime mover's type and size, positions of district heating and cooling pipelines and the operation of each system component. Besides considering the thermodynamic of each system component, the objective function also takes the facilities' cost, district heating and cooling network cost into consideration. Moreover, the influence of various amortization periods on the optimal solution is also discussed. Li et al. [193] model and optimize a system by an MINLP model. Analyses in this literature show that the optimal facility size and the economical performance of the whole system mainly depend on the average energy demand. In [194], MILP is used to model and optimize a CCHP system with a thermal storage system installed and to minimize the ATC. In this literature, the effect of legal constraints and different operation modes on the optimal design is also discussed. In [195], the authors construct an MINLP model for increasing the power production in a small-scale CHP plant. This CHP plant is driven by a steam Rankine process fired by biomass fuel. Using the MINLP, due to the complicated decision-making process in the system, the optimization problem is modelled to be a nonconvex problem. This problem is solved several times to filter out suboptimal solutions and to find out the most likely global optimal solution. This model is also tested on four existing CHP plants, in which the result shows that, by adding a two-stage district heat exchanger, a preheater, a steam reheater and a fuel dryer, the electric efficiency and power to heat ratio can be increased. Arcuri et al. [38] carry out a mixed integer programming model for the optimization of a CCHP system in a hospital. The optimization results, including short-term optimization and long-term optimization, give the optimal plant design, i.e., facility sizes and running conditions. With the proposed optimization approach, the case study result shows that, by utilizing size optimized heat pumps, the trigeneration system can be improved from economic, energetic and environmental aspects. Li et al. [196] thermoeconomically optimize a distributed trigeneration system by considering thermodynamic, economic and GHG emissions aspects. This optimization includes the system configuration and operation strategy. With the objective function set to be the system net present value (SNPV), MINLP is used to model the system and the genetic algorithm (GA) is adopted to solve it. An optimal solution is found under different economic and environmental legislation contexts in Beijing, China. Rong et al. [197] model a trigeneration system by the LP model with three components' characteristics. The objective function is set to be a combination of production and purchase cost, and the carbon cost. This problem is solved by the Tri-commodity algorithm, which is 36–58 times faster than an efficient Simplex code. Using the PGU capacity as the decision variable, Wang et al. [198] optimize a CCHP system by the GA. The objective function is set to be a weighted summation of PEC, ATC and CDE. Wang et al. [32] design an optimal operation strategy by optimizing the capacity of PGU, the capacity of heat storage tank, the on–off coefficient of PGU and the ratio of electric cooling to cool load using the particle swarm algorithm. All of the four decision variables are globally optimized, i.e., fixed once determined. The authors of this literature also compare the result of [32] to that of another literature [33]. In [33], only the PGU capacity and electric cooling to cool load ratio are considered to be decision variables. The objective function, which includes PESs, annual total cost savings (ATCSs) and CDER, is minimized by the GA. When compared to the GA, particle swarm algorithm converges faster and the result is better. Sheikhi et al. [199] conduct a cost–benefit analysis of a CHP system aiming to maximize the benefit-to-cost ratio. With the benefit-to-cost ratio incorporated into the objective function, using the concept of *energy hub*, the size and efficiency of this CHP system is optimized using the evolutionary-algorithmic (EA) approach. Kavvadias et al. [200] set up a multi-objective optimization problem for a trigeneration system, in which facilities sizes, pricing tariff schemes and the operation strategy are to be optimized according to realistic conditions. Pointing out the drawbacks of traditional load following strategies, the authors propose a new load following strategy, i.e., electric/heat equivalent load follow, which includes the continuous operation, peak shaving, electricity equivalent demand following and heat equivalent demand following. The optimization problem is solved by the multi-objective EA approach. Wang et al. [201] analyze the energy consumption and construct an environmental impact model, consisting of the global warming, acid precipitation and stratospheric ozone depletion, for an SP system and a CCHP system. The system capacity is optimized by the GA following the FEL strategy. In [202], the authors model a trigeneration system using a fuzzy multi-criteria decision-making model. Different configurations of trigeneration systems are compared with an SP system under this model. This fuzzy multi-criteria model can help to choose the optimal trigeneration configuration from technical, economical and some external (like the environmental) aspects. Piacentio et al. [203] propose a robust optimization method for a CCHP system based on energetic analyses. They point out and verify that, by considering the energetic behavior,

instead of improving the efficiency of an optimization algorithm, the optimization result can be significantly improved. Moran et al. [133] propose a thermoeconomic modelling approach, including the monthly operation cost, monthly fuel consumption, overall system efficiency, etc., for micro-scale CCHP systems in residential use. This model helps to choose the optimal prime mover type and capacity by taking the ratio of required heating and cooling loads to the required electric loads into consideration.

In recent years, a matrix modelling approach based on the *energy hub* begins to be used to model and optimize CCHP systems. In [36], the authors use a comprehensive approach to model a CCHP system in a compact matrix form. By adopting the sequential quadratic programming (SQP), the power flow and electric cooling to cool load ratio are optimized. The case study in [36] shows that, compared to conventional operation strategies, the proposed optimal power flow and operation strategy can well control the CCHP system to achieve less PEC, ATC and CDE. In [204], Chicco et al. propose a matrix modelling approach for a small-scale trigeneration system and optimize the operation strategy for it. The model is built by introducing the concepts of efficiency matrices, dispatch factors, interconnection matrices and input-to-output connectivity matrix. A depth-first manner is adopted to construct the overall plant efficiency matrix. In the optimization problem, NP techniques are used to obtain an optimal solution. In 2005, Geidl et al. [205] proposed a general matrix modelling and optimization approach for an energy system with various energy carriers. The optimization problem is a non-linear, multi-variable and inequality-constrained problem, which can be solved by the NP algorithm. In a later work of Geidl et al. [206], they use the concept of *energy hub* [207] to model the system by introducing the dispatch factors and coupling matrix. The dispatch and power flow are optimized by using the Karush–Kuhn–Tucker (KKT) conditions in order to minimize the total energy cost. The marginal cost is used to solve the KKT conditions. Using the same modelling approach, the optimization problem is solved by MATLAB *fmincon.m* in [208]. Ghaebi et al. [209] model a CCHP system using the TRR model to exergoeconomically optimize the cost of the total system production. Diverse parameters, including the air compressor pressure ratio, gas turbine inlet temperature, temperature in the heat recovery system, steam pressure, etc., are involved in this model The GA is adopted to solve for the optimal solution. Effects of the decision variables on different objective functions are also discussed in their work.

5.4. Sizing

Besides system configuration, operation strategy design, another equally important problem involved in the CCHP system is the facility sizing. As we all know, in the configuration step, one chooses prime movers in a vague way, i.e., no accurate rated power is chosen. For instance, when designing a small-scale CCHP system, whose capacity is in the range of 20 kW–1 MW, but what is the specific value on earth? An appropriate operation strategy must depend on the facility size. Except for the PGU, other facilities' sizes can be determined by the required output. However, the PGU size should not be too small, which will make a CCHP system degrades to an SP system and will cause more purchasing on electricity from local grid; this size should also not be too large, for high capital cost and low partial load efficiency. In many cases, the facility sizing problem can be inherently included in the modelling and optimization procedure. However, once the system configuration and operation strategy are designed, only the facility is to be sized to make the whole system efficient, economical and environmental friendly. In [210], the authors examine the influence of different prime mover sizes and different operation strategies on the performance of the CCHP system. They validate three different sizes of the natural gas reciprocating engines under three different classical operation strategies, i.e., FTL, FEL and following constant load (FCL). Different from other work, they use the actual market prices of electricity and natural gas instead of the flat one to minimize the CCHP performance indicators, i.e., cost, PEC and CDE, by optimizing the engine size. They point out that the optimal prime mover size would vary according to different evaluation criteria. Sclafani et al. [211] discussed the challenges of matching and sizing for the CCHP system, due to the strong and frequently varying load conditions, from both the operation-related and weather-related aspects. In order to mitigate the part-load issues and address the system flexibilities, the load profiling strategies are adopted to optimize the selection and sizing of the prime mover. Liu et al. [181] adopt the enumeration algorithm to obtain the optimal size of the PGU under the proposed "balance" space-based optimal operation strategy. In [164], the authors investigate the impact of the carbon tax on the sizing and operation strategy design of a medium-scale CHP system based on the IC engine. The thermo-economic approach (annual cost flow approach) is used to optimize the IC engine capacity. In this work, under three operation modes, i.e., one-way connection, two-way connection and heat demand following, the gas engine and diesel engine are sized to minimize the net annual cost. Shaneb et al. [212] model a μCHP plant with a generic deterministic LP model to minimize the annual cost. During the process of the optimization, the optimal size of the CHP unit and the size of the back-up heater can be obtained simultaneously. The sizing of the μCHP system can be completed either by the maximum rectangle method, which is to cover the average energy demand instead of the peak demand; or by LP. Different sizing results according to different prime movers, including IC engine, stirling engine, SOFC and PEMFC, are also presented. Harrod et al. [213] provide a sizing analysis on the wood waste biomass-fired stirling engine based CCHP system in a small office building. From their analyses, the characteristics of the prime mover, including the capacity and electrical efficiency, have a significant influence on the cost and PEC of the CCHP system. They also point out that the optimal engine size, which aims to reduce the cost, is always larger than that of the reference system, which can result in a larger PEC. Thus, the trade-off between the cost and the PEC should be taken into consideration when determine the optimal engine size. In [214], Ren et al. adopted the MINLP to model a residential CHP system, which includes a storage tank and a back-up boiler. In the optimization process, the CHP system capacity is selected and the operating schedules are determined in order to minimize the annual overall cost of the energy system. They also analyze the sensitivity of the natural gas prices, electricity prices, carbon tax rates and electricity buy-back prices on the optimal CHP system capacity. Besides the prime mover, the capacity of the storage tank is also optimized to reach a good trade-off between the flexible storage management and heat loss to the surroundings. Zhang et al. [215] also formulate the sizing problem of the CHP system as an MINLP problem constrained by the energy demands, facility performance characteristics and the power flow in the whole system. The objective function is set to be the ATC by considering the operation strategy. In [216], a gas-fired grid-connected cogeneration system, which includes an absorption chiller and a thermal storage system, is modelled as an MINLP model. Newton–Raphson and conjugate method with tangent estimates and forward derivatives are used to search for the optimal facility size aiming to minimize the operational cost. The best feasible practical solution is determined by the dynamic programming principle. Financial analysis, including the payback period and internal rate of return, is also reported in this work. Similar as [190], Rubio et al. [217] use the superstructure concept to choose the optimal size, which includes the

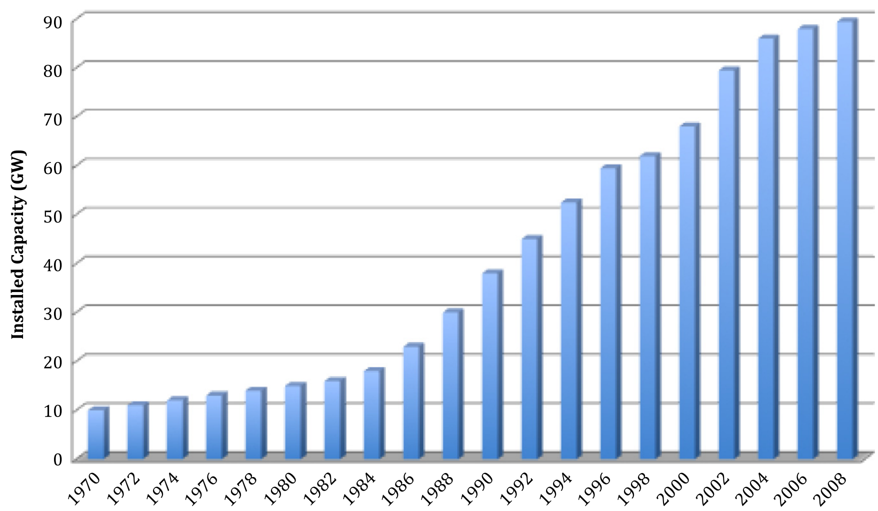

Fig. 6. U.S. CHP/CCHP development from 1970 [220].

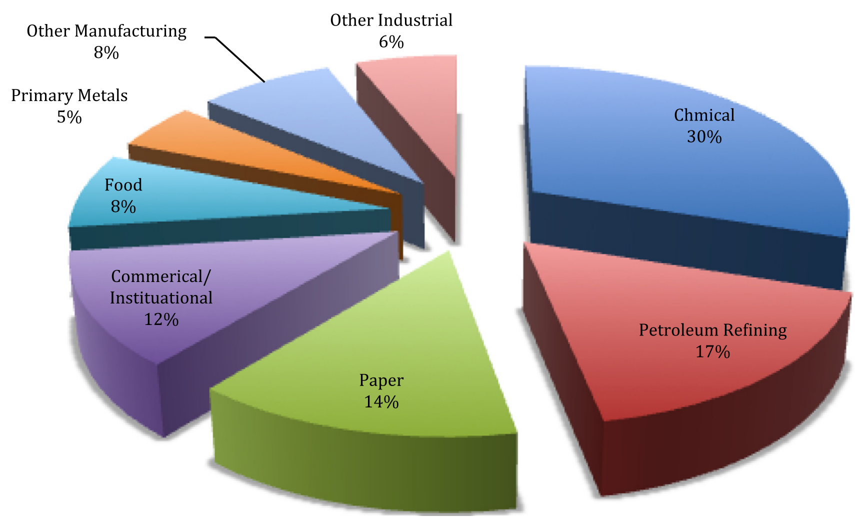

Fig. 7. The installed capacity of CHP/CCHP plants classified by applications in the U.S.

net power of the prime mover, cooling capacity of thermal activated facility and fresh water capacity of desalting unit, of a polygeneration system. The objective function is set to be the net present value, which is equally constrained by the energy and mass balance, and unequally constrained by the PESs, GHG emissions and legal framework aspects, and is solved as an MINLP problem. Sensitive analyses based on the prices of electricity, fuel and water are also provided in this work. In [218], aggregate thermal demand method (ATD_e method) is adopted to estimate the PESs. In addition, the estimation of PES, which is used for the sizing problem, in which the annual PES strategy is adopted. The PES strategy can combine both of the economical and environmental considerations. The most advantageous of this work is the simple calculation method, in which only a few global data representative is needed. In [219], using the concept of energy hub, Sheikhi et al. modelled the CCHP system optimization problem by an NP model. Aiming to achieve the maximum net benefit, the operation point of the energy hub and the size of prime mover, absorption chiller, auxiliary boiler and heating storage devices are optimized by solving the nonlinear programming in GAMS software. In addition, a financial analysis, which includes the net present value and internal rate of return, is conducted using the technique of discounted cash flow analysis.

6. Development and barriers of CHP/CCHP systems in representative countries

6.1. The United States

The U.S. government began to develop CHP/CCHP plants since 1978, when the Public Utility Regulatory Policy Act (PURPA) was proposed. In the PURPA, utilities are required to interconnect with and purchase electricity from cogeneration systems, in order to give industrial and institutional users access to the grid and allow excess electricity to be sold back. With the help of the PURPA and the federal tax credit for CHP investment, the installed capacity of CHP/CCHP systems grew to 45 GW in 1995 from 12 GW in 1980. Due to the intense competition and instability in the electricity market, the development of CHP/CCHP plants slowed down in 1990s. Only 1 GW installed capacity increased from 1995 to 1998. To boost the development, together with the Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE) proposed the “Combined cooling heating & power for buildings 2020 vision”, which aimed to double the installed capacity in 2010. Following the proposed document, the installed capacity grew significantly to 56 GW in 2001. Then in 2004, with a total installed capacity of 80 GW, the goal of 92 GW has been almost achieved.

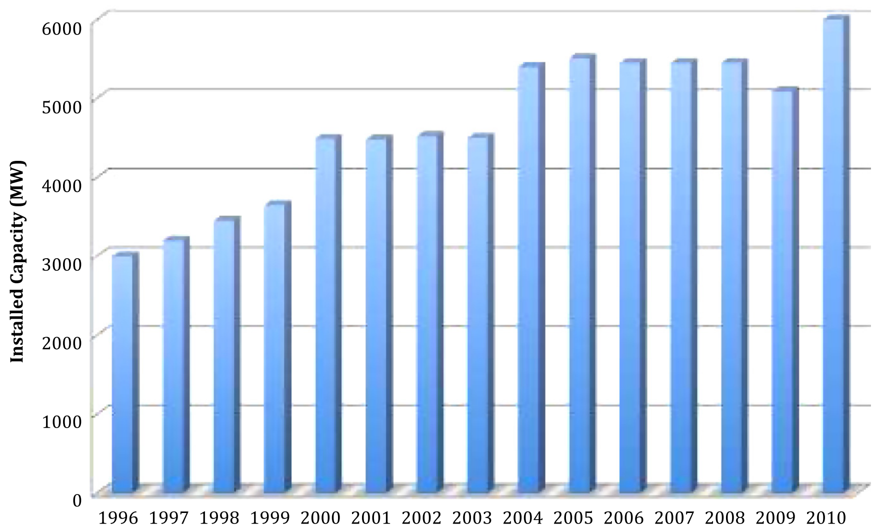

Fig. 8. The CHP/CCHP installed capacity in the UK [223].

In 2009, after the Energy Policy Act in 2005, the installed capacity has achieved 91 GW. The development trend of the U.S. CHP/CCHP installed capacity from 1970 can be shown in Fig. 6. Till 2011, as shown in Fig. 7, 30% CHP/CCHP installed capacity is used in chemical industries, 17% is used for petroleum refining, 14% for paper industries, 12% for commercial or institutional buildings, 8% for food manufacturing, 8% for other manufacturing, 5% for primary metals industries and 6% for other industries. According to “the White Paper on CHP in a Clean Energy Standard” [221], the U.S. DOE aims to have an 11% increase, from current 9%, of CHP share of the U.S. electric power by 2030. By doing so, 60% projected increase in U.S. carbon emissions can be avoided; over 1 million new, highly skilled jobs can be created; and $234 billion in new investment can be generated.

However, there still exist some barriers to further develop CHP/CCHP plants in the U.S. The first one is the high capital investment of CHP/CCHP plants. A firm may not have enough budgets to invest in such a high capital cost plant; or, if not sure about the payback of such a plant, it still cannot invest in it. Second, to keep a connection with the utility grid to supply power needs beyond the self-generation capacity, extra charges will be made for this connection. This will with no doubt reduce the money-saving potential of CHP/CCHP plants. Third, nonuniform interconnection standards make it difficult for manufacturers to provide CHP/CCHP components. In addition, some policies, such as the Clean Air Act's New Source Review, only consider short-term carbon emissions instead of a long-term and overall vision. Because “the CHP/CCHP can increase onsite air emissions even as it reduces total emissions associated with the facilities heat and electricity consumption” [222], the development of CHP plants can be restricted by such regulations. Finally, further theoretical research, development and demonstrations should be conducted to find out more efficient operation modes, system configurations and system components.

6.2. *The United Kingdom*

In the United Kingdom, the number and installed capacity of CHP/CCHP plants increased dramatically from 1999 to 2000, during which the UK government took methods of fiscal incentives, grant support, regulatory framework, promotion of innovation, and government leadership and partnership to support the development of CHP/CCHP. Before 2000, the installed capacity kept around 3.5 GW, while in 2000, it increased to 4.5 GW. From then on, the UK government continuously drafted a series of policies to target at achieving 10 GW *of good quality* installed CHP plants. In the end of 2010, the total installed capacity in the UK reached 6 GW, which can be shown in Fig. 8. Classified by applications, as shown in Fig. 9, 38% of the installed capacity is used for oil and gas terminals and refineries, another 30% is used for chemical industries and only 4% is used for community usage, etc. In [224], it is also pointed out that “the *of good quality* CHP will be a key technology in helping to deliver our carbon budgets while the grid decarbonizes, and will still play a pivotal role in providing secure and cost-effective energy supplies, particularly for industry. The government will continue to promote the development of *of good quality* CHP in the UK”.

Meanwhile, there are still some obstacles for CHP/CCHP to be further developed in the UK. The first one is the inconsistency between incentive frameworks and market signals. One significant character of the UK market is the price volatility. The differential between electricity and gas prices put the investment of CHP/CCHP in an uncertain situation. This issue may be addressed by the Climate Change Levy. Second, in theory, the establishment of the carbon market should directly support the expansion of CHP/CCHP capacity. However, due to the unstable carbon price and uncertain allocation arrangements of CHP/CCHP plants, this theory has not yet been verified. Only with a robust price signal and a stable carbon market, the direct relationship between the CHP/CCHP expansion and carbon market can be established. In addition, lacking of locational signals for heat utilization also shield the development of CHP/CCHP plants. Moreover, to achieve the peak efficiency, heat transmission and distribution network should be completed. Finally, insufficient incentive to investment in heat distribution infrastructures also slows down the pace of the CHP/CCHP development in the UK.

6.3. *The People's Republic of China*

Due to the Reform and Open Up to the Outside World Policy, the rapid development of economics, technology and industry leads China to be the well known second-largest energy consumer and carbon emitter in the world. To solve the problem of the increasing demand for primary energy, China has issued a series of policies, including the Energy Saving Law, the Renewable Energy Law, the Air Pollution Prevention Law and the Environment Protection Law, to support the development of CHP/CCHP plants since 1980s. In addition, accompanying with those laws, some standards, e.g., Energy Efficiency Standards for Buildings, Energy

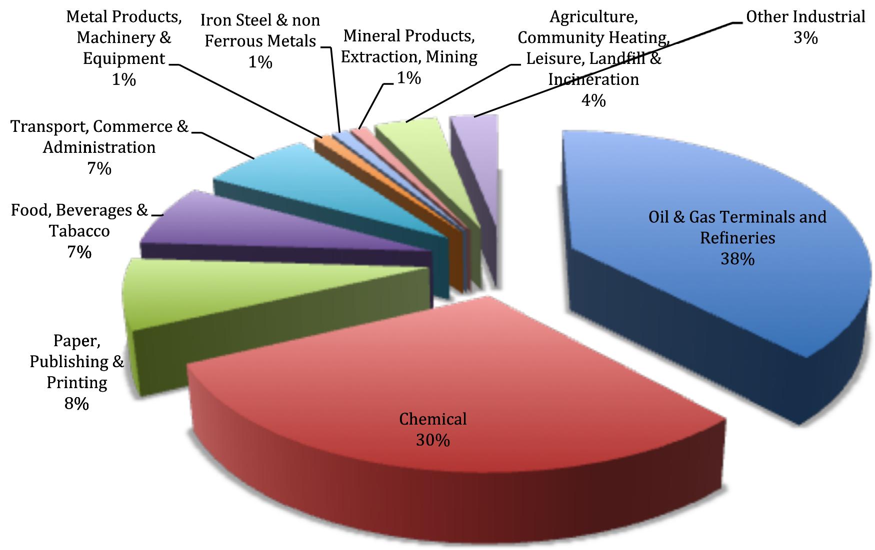

Fig. 9. The installed capacity of CHP plants classified by applications in UK [223].

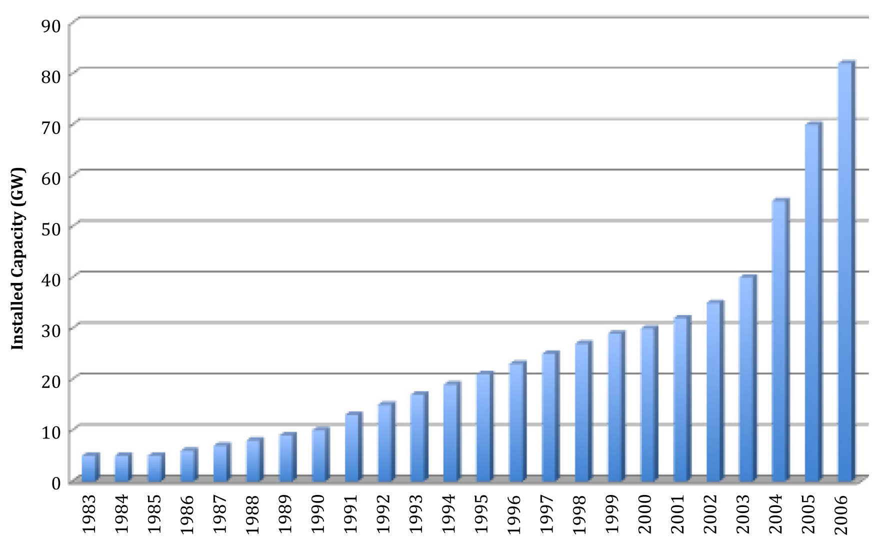

Fig. 10. The installed capacity of CHP in China [225].

Efficiency Standards for Appliances, etc.; and some dedicated funds, subsidies and discounted loans for energy efficiency investments are also carried out by the Chinese government. These steps make China become the second-largest country in terms of the installed CHP capacity. In 1986, the Notice on the Report Regarding the Work on Strengthening Urban District Heat Supply Management enhanced the urban district heating supply management. The China Energy Conservation Law, drafted in 1997, listed CHP as a key national energy conservation technology that should be encouraged. The 1998 Some Regulations for CHP Development considered the ratio between heat and electricity as an important indicator to define and approve new CHP. In 2004, the China Medium- and Long-Term Energy Development Plan considered CHP/district heating and cooling (CHP/DHC) as an encouraging technology and named CHP as one of the 10 key national energy conservation programmes. In 2006, the NDRC's China Energy Conservation Technology Policy Outline recommended that CHP should take place of small heating boilers; and they should be developed in large- and medium-sized cities in north heating areas. The 2007 Implementation Scheme of the National 10 Key Energy Conservation Projects further specified important applications and supporting policies for CHP. Another important policy that could boost the development of CHP/CCHP plants in China is the Industrial Guidance Catalogue for Foreign Investments drafted in 2007. This policy encouraged foreign investments and operations of CHP/CCHP power stations in China.

In 1990, the total installed CHP capacity in China was only 10 GW. After ten years' construction and development, with an annual growth rate of 11.6%, a goal of 30 GW installed capacity was achieved in 2000. By 2005, almost 70 GW of capacity had been installed. Till 2006, over 2600 CHP plants with over 80 GW capacity were installed in China. The development trend can be shown in Fig. 10. The share of CHP capacity in thermal power generation in China is shown in Fig. 11.

With no doubt, CHP/CCHP is a promising solution for the energy short and air pollution problem, however, there are still some barriers to further develop CHP/CCHP plants in China. The first one to be solved in urgent is the reform of energy price policies. In China, even though the coal price, which increases dramatically, is based on the market, the price of electricity, which slightly increased, is decided by the government. Unbalance increasing rates between the prices of coal and electricity severely

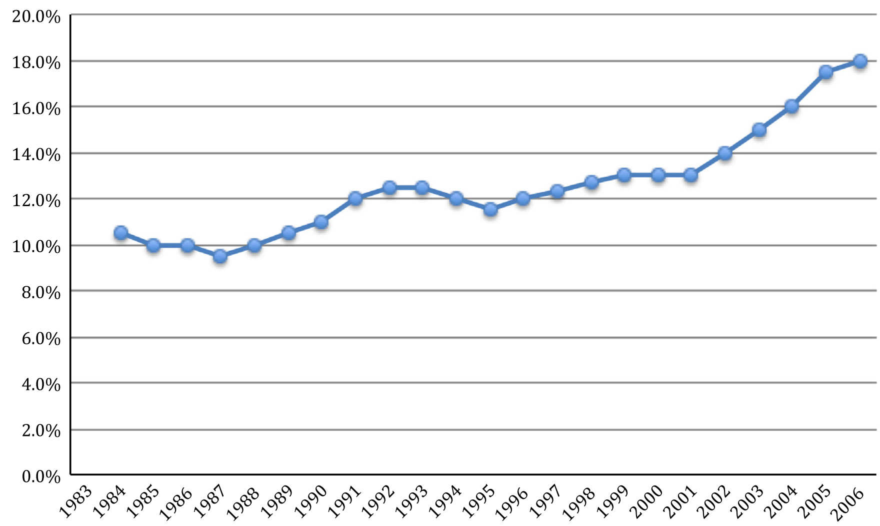

Fig. 11. Share of CHP capacity in thermal power generation [225].

restrict the development of CHP/CCHP in China. Besides the reform of energy price policies, heating and power sector reforms also need to be taken into consideration. Not only the economic and price aspect, but also some favorable fiscal and tax incentives should be proposed to support the construction of CHP/CCHP. In addition, since some newly-built CHP projects are operating only in thermal generation mode after established, energy efficiencies of these plants are significantly reduced. Thus, the monitoring and enforcement of the government should be enhanced. Finally, due to an increasing number of large and more efficient CHP plants, some old, small but quite efficient CHP plants are forced to shut down. Hence, policies that suitable for the small but efficient units should be drafted to keep the whole efficiency.

7. Conclusion

This paper elaborately presents the state of art of CCHP systems. The CCHP, which can provide the cooling energy by adopting the thermally activated technology, is a concept extended from the CHP system. To construct an economical and efficient CCHP system, facilities type should be determined first according to the local resources, and current and future energy market. Different types of prime movers and thermally activated technologies are introduced. The system configuration varies according to different usages, including commercial buildings, residential buildings, supermarkets, universities, hospitals, etc. Some classical CHP/CCHP configurations classified by prime mover types and system capacities are also introduced in this paper. With the determined facility type and system configuration, to achieve the optimal operation status, the operation strategy, power flow and the facilities capacity should be optimized. The current research on the optimal operation strategy design, power flow optimization and sizing problem are reviewed in this paper. As many countries have begun to develop CHP/CCHP systems, development history and current status of three representative countries, i.e., the United States, the United Kingdom and the People's Republic of China, are presented. From these three countries, even the situations are a little bit different, to further develop the CCHP technology in the whole world, some similar obstacles and solutions are discussed. The high capital cost, government supporting policies, favorable fiscal and tax incentives and further research and demonstration should be paid more attention. In the future development of CHP/CCHP system, some renewable energy is promised to be incorporated into the system. Wind energy and solar energy, including PV and thermal storage, has been increasingly investigated recently.

References

[1] Tatsumi I. Applicability of micro gas turbine as distributed generation and its connection to utility power grid. J Gas Turbine Soc Jpn 2001;29(3):141–5.
[2] Oliveira AC, Afonso C, Matos J, Riffat S, Nguyen M, Doherty P. A combined heat and power system for buildings driven by solar energy and gas. Appl Therm Eng 2002;22(6):587–93.
[3] Lior N, Zhang N. Energy, exergy, and second law performance criteria. Energy 2007;32(4):281–96.
[4] Bourgeoisa TG, Hedmanb B, Zalcmanc F. Creating markets for combined heat and power and clean distributed generation in New York State. Environ Pollut 2003;123(3):451–62.
[5] Huangfu Y, Wu J, Wang R, Kong X, Wei B. Evaluation and analysis of novel micro-scale combined cooling, heating and power (MCCHP) system. Energy Convers Manag 2007;48(5):1703–9.
[6] Bilgen E. Exergetic and engineering analyses of gas turbine based cogeneration systems. Energy 2000;25(12):1215–29.
[7] Kong XQ, Wang RZ, Huang XH. Energy optimization model for a CCHP system with available gas turbine. Appl Therm Eng 2005;25(2–3):377–91.
[8] Khana K, Rasulb M, Khan M. Energy conservation in buildings: cogeneration and cogeneration coupled with thermal energy storage. Appl Energy 2004;77(1):15–34.
[9] Havelsky V. Energetic efficiency of cogeneration systems for combined heat, cold and power production. Int J Refrig 1999;22(6):479–85.
[10] Wu DW, Wang RZ. Combined cooling, heating and power: a review. Progr Energy Combust Sci 2006;32(5–6):459–95.
[11] Xu J, Sui J, Li B, Yang M. Research, development and the prospect of combined cooling, heating, and power systems. Energy 2010;35(11):4361–7.
[12] Hernandez-Santoyoa J, Sanchez-Cifuentes A. Trigeneration: an alternative for energy savings. Appl Energy 2003;76(1–3):119–27.
[13] Energetics Incorporated. Market assessment of distributed energy in new commercial and institutional buildings and critical infrastructure facilities. Technical report. Energetics Incorporated; 2006.
[14] Dong L, Liu H, Riffat S. Development of small-scale and micro-scale biomass-fuelled CHP systems – a literature review. Appl Therm Eng 2009;29(11–12):2119–26.
[15] d'Accadia MD, Sasso M, Sibilio S, Vanoli L. Micro-combined heat and power in residential and light commercial applications. Appl Therm Eng 2003;23(10):1247–59.
[16] Lasseter RH, Paigi P. Microgrid: a conceptual solution. In: Power electronics specialist conference, vol. 6. 2004. p. 4285–90.
[17] Martens A. The energetic feasibility of CHP compared to the separate production of heat and power. Appl Therm Eng 1998;18(11):935–46.
[18] Balli O, Aras H, Hepbasli A. Exergoeconomic analysis of a combined heat and power (CHP) system. Int J Energy Res 2008;32(4):273–89.
[19] Pilavachi PA, Roumpeas CP, Minett S, Afgan NH. Multi-criteria evaluation for CHP system options. Energy Convers Manag 2006;47(20):3519–29.
[20] Fumo N, Mago PJ, Chamra LM. Cooling, heating, and power energy performance for system feasibility. Proc Inst Mech Eng Part A J Power Energy 222:2008;347–54.
[21] Carrasco JM, Franquelo LG, Bialasiewicz JT, Galvan E, Guisado RCP, Prats MAM, et al. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Trans Ind Electron 2006;53(4):1002–16.

[22] Weisser D, Garcia RS. Instantaneous wind energy penetration in isolated electricity grids: concepts and review. Renew Energy 2005;30(8):1299–308.
[23] Dincer I. Renewable energy and sustainable development: a crucial review. Renew Sustain Energy Rev 2000;4(2):157–75.
[24] U.S. Department of Energy. Types of fuel cells [online]; 2011.
[25] Agostini P, Botteon M, Carraro C. A carbon tax to reduce CO_2 emissions in Europe. Energy Econ 1992;14(4):279–90.
[26] Floros N, Viachou A. Energy demand and energy-related CO_2 emissions in Greek manufacturing: assessing the impact of a carbon tax. Energy Econ 2005;27(3):387–413.
[27] Cnossen S. Tax policy in the European Union: a review of issues and options. FinanzArchiv/Public Finance Anal 2001;58(4):466–558.
[28] Bernard A, Vielle M, Viguier L. Carbon tax and international emissions trading: a swiss perspective. Adv Global Change Res 2005;22:295–319.
[29] Shrestha R, Pradhan S, Liyanage MH. Effects of carbon tax on greenhouse gas mitigation in Thailand. Climate Policy 2008;8(1):S140–55.
[30] Alanne K, Saari A. Distributed energy generation and sustainable development. Renew Sustain Energy Rev 2006;10(6):539–58.
[31] Driesen J, Katiraei F, Leuven KU. Design for distributed energy resources. IEEE Power Energy Mag 2008;6(3):30–40.
[32] Wang J, Zhai Z, Jing Y, Zhang C. Particle swarm optimization for redundant building cooling heating and power system. Appl Energy 2010;87(12):3668–79.
[33] Wang J, Jing Y, Zhang C. Optimization of capacity and operation for CCHP system by genetic algorithm. Appl Energy 2010;87(4):1325–35.
[34] Li Y, Wang RZ. Adsorption refrigeration: a survey of novel technologies. Recent Patents Eng 2007;1(1):1–21.
[35] Jones JA. Sorption refrigeration research at JPL/NASA. Heat Recovery Syst CHP 1993;13(4):363–71.
[36] Liu M, Shi Y, Fang F. Optimal power flow and PGU capacity of CCHP systems using a matrix modelling approach. Appl Energy 2013;102:794–802.
[37] Goodell M. The advantages of cogeneration and trigeneration [online] [cited ⟨http://www.trigeneration.com/⟩]; 2011.
[38] Arcuri P, Florio G, Fragiacomo P. A mixed integer programming model for optimal design of trigeneration in a hospital complex. Energy 2007;32(8):1430–47.
[39] Ge Y, Tassou S, Chaer I, Suguartha N. Performance evaluation of a trigeneration system with simulation and experiment. Appl Energy 2009;86(11):2317–26.
[40] Maidment GG, Tozer RM. Combined cooling heat and power in supermarkets. Appl Therm Eng 2002;22(6):653–65.
[41] Gao L, Wu H, Jin H, Yang M. System study of combined cooling, heating and power system for eco-industrial parks. Int J Energy Res 2008;32(12):1107–18.
[42] WADE. 4,600 kWe gas turbine CCHP Shanghai Pudong International Airport. Technical report. WADE; 2011.
[43] Huang D. Assessment on barriers of CHP/trigeneration promotion and potential countermeasure in China. Technical report. Zhejiang Energy Research Institute (ZERI); 2004.
[44] Li H, Fu L, Geng K, Jiang Y. Energy utilization evaluation of CCHP systems. Energy Build 2006;38(3):253–7.
[45] Wikipedia. Reciprocating engine [online]; 2011.
[46] Energy and Environmental Analysis, Inc. Technology characterization: reciprocating engines. Technical report. Energy and Environmental Analysis, Inc. an ICF Company; 2008.
[47] Onovwiona H, Ugursal V. Residential cogeneration systems: review of the current technology. Renew Sustain Energy Rev 2005;10(5):389–431.
[48] Knight I, Ugursal V. Residential cogeneration systems: a review of the current technologies, a report of annex 42 of the international energy agency, energy conservation in buildings and community systems programme. Technical report; 2005.
[49] Onovwiona HI, Ugursal VI, Fung AS. Modeling of internal combustion engine based cogeneration systems for residential applications. Appl Therm Eng 2007;27(5–6):848–61.
[50] HONDA Motor CO. Honda to begin practical tests of small household cogeneration unit [online]; 2001.
[51] Bidini G, Desideri U, Saetta S, Bocchini PP. Internal combustion engine combined heat and power plants: case study of the University of Perugia power plant. Appl Therm Eng 1998;18(6):401–12.
[52] Jalalzadeh-Azar AA, Slayzak S, Judkoff R, Schamuser T, DeBlasio R. Performance assessment of a desiccant cooling system in a CHP application incorporating an IC engine. Int J Distrib Energy Resour 2004;1(2):163–84.
[53] Longo GA, Gasparella A, Zilio C. Analysis of an absorption machine driven by the heat recovery on an I.C. reciprocating engine. Int J Energy Res 2005;29(8):2005.
[54] Talbi M, Agnew B. Energy recovery from diesel engine exhaust gases for performance enhancement and air conditioning. Appl Therm Eng 2002;22(6):693–702.
[55] Riley JM, Probert SD. Carbon-dioxide emissions from an integrated small-scale CHP and absorption chiller system. Appl Energy 1998;61(4):193–207.
[56] Wikipedia. Internal combustion engine [online]; 2011.
[57] Energy and Environmental Analysis, Inc. Technology characterization: gas turbines. Technical report. Energy and Environmental Analysis, Inc. an ICF Company; 2008.
[58] Poullikkas A. An overview of current and future sustainable gas turbine technologies. Renew Sustain Energy Rev 2005;9(5):409–43.
[59] Pilavachi P. Power generation with gas turbine systems and combined heat and power. Appl Therm Eng 2000;20(15–16):1421–9.
[60] Maidment G, Zhao X, Riat S. Combined cooling and heating using a gas engine in a supermarket. Appl Energy 2001;68(4):321–35.
[61] Sue D-C, Chuang C-C. Engineering design and exergy analyses for combustion gas turbine based power generation system. Energy 2004;29(8):1183–205.
[62] Kong XQ, Wang RZ, Wu JY, Huang XH, Huangfu Y, Wu DW, et al. Experimental investigation of a micro-combined cooling, heating and power system driven by a gas engine. Int J Refrig 2005;28(7):977–87.
[63] Wikipedia. Steam turbine [online]; 2011.
[64] Energy and Environmental Analysis, Inc. Technology characterization: steam turbines. Technical report. Energy and Environmental Analysis, Inc. an ICF Company; 2008.
[65] Energy and Environmental Analysis, Inc. Technology characterization: microturbines. Technical report. Energy and Environmental Analysis, Inc. an ICF Company; 2008.
[66] Energy Nexus Group. Technology characterization: microturbines. Technical report. Energy Nexus Group; 2002.
[67] Pilavachi PA. Mini- and micro-gas turbines for combined heat and power. Appl Therm Eng 2002;22(18):2003–14.
[68] Balli O, Aras H. Energetic and exergetic performance evaluation of a combined heat and power system with the micro gas turbine (MGTCHP). Int J Energy Res 2007;31(14):1425–40.
[69] Tassou SA, Chaer I, Sugiartha N, Ge YT, Marriott D. Application of trigeneration systems to the food retail industry. Energy Convers Manag 2007;48(11):2988–95.
[70] Karellas S, Karl J, Kararas E. An innovative biomass gasification process and its coupling with microturbine and fuel cell systems. Energy 2008;33(2):284–91.
[71] Rizy DT, Zaltash A, Labinov SD, Petrov AY, Fairchild PD. DER performance testing of a microturbine-based combined cooling, heating, and power (CHP) system. In: Power system 2002 conference"Impact of distributed generation". 2002.
[72] Bruno JC, Ortega-López V, Coronas A. Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: case study of a sewage treatment plant. Appl Energy 2009;86(6):837–47.
[73] Hwang Y. Potential energy benefits of integrated refrigeration system with microturbine and absorption chiller. Int J Refrig 2004;27(8):816–29.
[74] Velumani S, Guzman CE, Peniche R, Vega R. Proposal of a hybrid CHP system: SOFC/microturbine/absorption chiller. Int J Energy Res 2010;34(12):1088–95.
[75] Liao X, Radermacher R. Absorption chiller crystallization control strategies for integrated cooling heating and power systems. Int J Refrig 2007;30(5):904–11.
[76] Sugiartha N, Tassou SA, Chaer I, Marriott D. Trigeneration in food retail: an energetic, economic and environmental evaluation for a supermarket application. Appl Therm Eng 2009;29(13):2624–32.
[77] Medrano M, Mauzey J, McDonell V, Samuelsen S, Boer D. Theoretical analysis of a novel integrated energy system formed by a microturbine and an exhaust fired single-double effect absorption chiller. Int J Thermodyn 2006;9(1):29–36.
[78] Vidal A, Bruno JC, Best R, Coronas A. Performance characteristics and modelling of a micro gas turbine for their integration with thermally activated cooling technologies. Int J Energy Res 2007;31(2):119–34.
[79] Huicochea A, Rivera W, Gutiérrez-Urueta G, Bruno JC, Coronas A. Thermodynamic analysis of a trigeneration system consisting of a micro gas turbine and a double effect absorption chiller. Appl Therm Eng 2011;31(16):3347–53.
[80] Obernberger I, Carlsen H, Biedermann F. State-of-the-art and future developments regarding small-scale biomass CHP systems with a special focus on ORC and stirling engine technologies. In: International Nordic bioenergy conference. 2003. p. 1–7.
[81] Wikipedia. Stirling engine [online]; 2012.
[82] Harrison J. Micro combined heat and power. Technical report. EA Technology; 2002.
[83] Vineeth CS. Stirling engines: a begineers guide; 2011.
[84] Kong RZWXQ, Huang XH. Energy efficiency and economic feasibility of CCHP driven by stirling engine. Energy Convers Manag 2004;45(9–10):1433–42.
[85] Biedermann F, Carlsen H, Schoch M, Obernberger I. Operating experiences with a small-scale CHP pilot plant based on a 35 kW_{EL} hermetic four cylinder stirling engine for biomass fuels. Technical report. BIOS BIOENERGIESYSTEME GmbH; 2004.
[86] Aliabadi AA, Thomson MJ, Wallace JS, Tzanetakis T, Lamont W, Carlo JD. Efficiency and emissions measurement of a stirling-engine-based residential microcogeneration system run on diesel and biodiesel. Energy Fuels 2009;23(2):1032–9.
[87] Scarpete D, Uzuneanu K, Badea N. Stirling engine in residential systems based on renewable energy [online, cited ⟨http://www.wseas.us⟩].
[88] Khurmi RS, Sedha RS. Material science. New Delhi, India: S. Chand & Company Ltd.; 2010.
[89] Wang C, Nehrir MH. Distributed generation applications of fuel cells. In: Power systems conference: advanced metering, protection, control, communication, and distributed resources. 2006. p. 244–8.
[90] Stambouli AB, Traversa E. Fuel cells, an alternative to standard sources of energy. Renew Sustain Energy Rev 2002;6(3):295–304.
[91] Kordesch K, Simader G. Fuel cells and their applications. Wiley-VCH, Weinheim: 1996.

[92] Tse LKC, Wilkins S, McGlashan N, Urban B, Martinez-Botas R. Solid oxide fuel cell/gas turbine trigeneration system for marine applications. J Power Sources 2011;196(6):3149–62.
[93] Kazempoor P, Dorer V, Ommi F. Modelling and performance evaluation of solid oxide fuel cell for building integrated co- and polygeneration. Fuel Cells 2010;10(6):1074–94.
[94] Baniasadi E, Alemrajabi AA. Fuel cell energy generation and recovery cycle analysis for residential application. Int J Hydrog Energy 2010;35(17):9460–7.
[95] Verda V, Quaglia MC. Solid oxide fuel cell systems for distributed power generation and cogeneration. Int J Hydrog Energy 2008;33(8):2087–96.
[96] Al-Sulaiman FA, Dincer I, Hamdullahpur F. Exergy analysis of an integrated solid oxide fuel cell and organic Rankine cycle for cooling, heating and power production. J Power Sources 2010;195(8):2346–54.
[97] Al-Sulaiman FA, Dincer I, Hamdullahpur F. Energy analysis of a trigeneration plant based on solid oxide fuel cell and organic Rankine cycle. Int J Hydrog Energy 2010;35(10):5104–13.
[98] Yu Z, Han J, Cao X, Chen W, Zhang B. Analysis of total energy system based on solid oxide fuel cell for combined cooling and power applications. Int J Hydrog Energy 2010;35(7):2703–7.
[99] Kazempoor P, Dorer V, Ommi F. Evaluation of hydrogen and methane-fuelled solid oxide fuel cell systems for residential applications: system design alternative and parameter study. Int J Hydrog Energy 2009;34(20):8630–44.
[100] Malico I, Carvalhinho AP, Tenreiro J. Design of a trigeneration system using a high-temperature fuel cell. Int J Energy Res 2009;33(2):144–51.
[101] Braun RJ, Klein SA, Reindl DT. Evaluation of system configurations for solid oxide fuel cell-based micro-combined heat and power generators in residential applications. J Power Sources 2006;158(2):1290–305.
[102] Weber C, Koyama M, Kraines S. CO_2-emissions reduction potential and costs of a decentralized energy system for providing electricity, cooling and heating in an office-building in Tokyo. Energy 2006;31(14):3041–61.
[103] Colella WG, Timme R. Optimizing operation of stationary fuel cell systems (FCS) within district cooling and heating networks. In: ASME conference proceedings, vol. 263, 2010. p. 1–114.
[104] Margalef P, Samuelsen S. Integration of a molten carbonate fuel cell with a direct exhaust absorption chiller. J Power Sources 2010;195(17):5674–85.
[105] Bazzarri G. On the size effect in PAFC grid-connected plant. Appl Therm Eng 2006;26(10):1001–7.
[106] Deng J, Wang RZ, Han GY. A review of thermally activated cooling technologies for combined cooling, heating and power systems. Progr Energy Combust Sci 2011;37(2):172–203.
[107] Gosney WB. Principle of refrigeration. Cambridge, United Kingdom: Cambridge University Press; 1982.
[108] Srikhirim P, Aphornratana S, Chungpaibulpatana S. A review of absorption refrigeration technologies. Renew Sustain Energy Rev 2001;5(4):343–72.
[109] Marcriss RA, Gutraj JM, Zawacki TS. Absorption fluid data survey: final report on worldwide data. Technical report. Institute of Gas Technology; 1988.
[110] Stambler I. 4.6 MW plant with an indirect fired 2600 ton chiller at 76.8% efficiency. Gas Turbine World 2004;34(4):14–7.
[111] Marantan A. Optimization of integrated micro-turbine and absorption chiller systems in CHP for buildings application [Ph.D. thesis]. University of Maryland; 2002.
[112] Bassols J, Kuchelkorn B, Langreck J, Schneder R, Veelken H. Trigeneration in the food industry. Appl Therm Eng 2002;22(6):595–602.
[113] Critoph RE, Zhong Y. Review of trends in solid sorption refrigeration and heat pumping technology. Proc Inst Mech Eng Part E J Process Mech Eng 219:2005;285–300.
[114] Balaras CA, Grossman G, Henning H, Ferreria CAI, Podesser E, Wang L, et al. Solar air conditioning in Europe – an overview. Renew Sustain Energy Rev 2007;11(2):299–314.
[115] Kim DS, Ferreria CAI. Solar refrigeration options – a state-of-the-art review. Int J Refrig 2008;3(1):3–15.
[116] Wang RZ, Wu JY, Xu YX, Wang W. Performance researches and improvements on heat regenerative adsorption refrigerator and heat pump. Energy Convers Manag 2001;42(2):233–49.
[117] Li S, Wu JY. Theoretical research of a silica gel–water adsorption chiller in a micro combined cooling, heating and power (CCHP) system. Appl Energy 2009;86(6):958–67.
[118] Midwest CHP Application Center (University of Illinois at Chicago), Avalon Consulting, Inc. Combined heat and power source guide. Midwest CHP Application Center (University of Illinois at Chicago) and Avalon Consulting, Inc.; 2003.
[119] Mississippi Cooling, Heating, and Power (Micro-CHP) and Bio-fuel Center. Cooling, heating, and power for buildings (CHP-B) instructional module. Technical report. Department of Mechanical Engineering, Mississippi State University; 2004.
[120] Henning H-M, Pagano T, Mola S, Wiemken E. Micro tri-generation system for indoor air conditioning in the mediterranean climate. Appl Therm Eng 2007;27(13):2188–94.
[121] Fu L, Zhao XL, Zhang SG, Jiang Y, Li H, Yang WW. Laboratory research on combined cooling, heating and power (CCHP) systems. Energy Convers Manag 2009;50(4):977–82.
[122] Badami M, Portoraro A. Performance analysis of an innovative small-scale trigeneration plant with liquid desiccant cooling system. Energy Build 2009;41(11):1195–204.
[123] Easow R, Muley P. Micro-trigeneration:–the best way for decentralized power, cooling and heating. In: IEEE conference on innovative technologies for an efficient and reliable electricity supply (CITRES). 2010. p. 459–66.
[124] Southeast CHP Application Center. NC solar center integrated micro-CHP and solar system. Technical report. Southeast CHP Application Center.
[125] Angrisani G, Rosato A, Roselli C, Sasso M, Sibilio S. Experimental results of a micro-trigeneration installation. Appl Therm Eng 2012;38:78–90.
[126] Khatri KK, Sharma D, Soni SL, Tanwar D. Experimental investigation of CI engine operated micro-trigeneration system. Appl Therm Eng 2010;30(11–12):1505–9.
[127] Kong XQ, Wang RZ, Li Y, Huang XH. Optimal operation of a micro-combined cooling, heating and power system driven by a gas engine. Energy Convers Manag 2009;50(3):530–8.
[128] Gluesenkamp K, Hwang Y, Radermacher R. High efficiency micro trigeneration systems, 2012. http://dx.doi.org/10.1016/j.applthermaleng.2011.11.062.
[129] Ebrahimi M, Keshavarz A, Jamali A. Energy and exergy analyses of a micro-steam CCHP cycle for a residential building. Energy Build 2012;45:202–10.
[130] Cervone A, Romito DZ, Santini E. Technical and economic analysis of a micro-tri/cogeneration system with reference to the primary power source in a shopping center. In: International conference on clean electrical power. 2011. p. 439–45.
[131] Uzuneanu K, Scarpete D. Energetic and environmental analysis of a micro CCHP system for domestic use. In: 6th IASME/WSEAS international conference on Energy and Environment (EE '11). 2011. p. 322–7.
[132] Ameri M, Behbahaninia A, Tanha AA. Thermodynamic analysis of a tri-generation system based on micro-gas turbine with a steam ejector refrigeration system. Energy 2010;35(5):2203–9.
[133] Moran A, Mago PJ, Chamra LM. Thermoeconomic modeling of micro-CHP (micro-cooling, heating, and power) for small commercial applications. Int J Energy Res 2008;32(9):808–23.
[134] Deng J, Wang RZ, Wu J, Han G, Wu D, Li S. Exergy cost analysis of a micro-trigeneration system based on the structural theory of thermoeconomics. Energy 2008;33(9):1417–26.
[135] Arosio S, Guilizzoni M, Pravettoni F. A model for micro-trigeneration systems based on linear optimization and the Italian tariff policy. Appl Therm Eng 2011;31(14–15):2292–300.
[136] Tracy TJ. Design, modeling, construction, and flow splitting optimization of a micro combined heating, cooling, and power system [Master's thesis]. Florida State University; 2010.
[137] Palmero-Marrero AI, Oliveira AC. Performance simulation of a solar-assisted micro-tri-generation system: hotel case study. Int J Low-Carbon Technol 2011;6(4):309–17.
[138] Immovilli F, Bellini A, Bianchini C, Franceschini G. Solar trigeneration for residential applications, a feasible alternative to traditional microcogeneration and trigeneration plants. In: IEEE industry applications society annual meeting. 2008. p. 1–8.
[139] Huangfu Y, Wu JY, Wang RZ, Xia ZZ. Experimental investigation of adsorption chiller for micro-scale BCHP system application. Energy Build 2007;39(2):120–7.
[140] Northeast Clean Energy Application Center. Cooley Dickinson – 500 kW biomass CHP plant. Technical report. Northeast Clean Energy Application Center; 2011.
[141] Pacific Region CHP Application Center. East Bay Municipal Utility District – 600 kW microturbine CHP/chiller system. Technical report. Pacific Region CHP Application Center; 2011.
[142] Northeast CHP Application Center. Smithfield gardens assisted living community – 75 kW CHP plant. Technical report. Northeast CHP Application Center; 2011.
[143] Pacific Region CHP Application Center. Vineyard 29 – 120 kW microturbine/chiller system. Technical report. Pacific Region CHP Application Center; 2011.
[144] Badami M, Ferrero M, Portoraro A. Experimental assessment of a small-scale trigeneration plant with a natural gas microturbine and a liquid desiccant system. In: 2nd European conference on polygeneration. 2011. p. 1–10.
[145] Katsigiannis PA, Papadopoulos DP. A systematic computational procedure for assessing small-scale cogeneration application schemes. In: International conference on power engineering, energy and electrical devices. 2007. p. 201–6.
[146] Northeast CHP Application Center. Harbec plastics – 750 kW CHP application. Technical report. Northeast CHP Application Center; 2011.
[147] Pacific Region CHP Application Center. The Ritz-Carlton Hotel in San Francisco – 240 kW microturbine/absorption chiller system. Technical report. Pacific Region CHP Application Center.
[148] de Boer R, Smeding SF, Grisel RJH. Performance of a silica-gel+water adsorption cooling system for use in small-scale tri-generation applications. In: Heat powered cycles conference. 2006. p. 1–13.
[149] Chicco G, Mancarella P. Planning aspects and performance indicators for small-scale trigeneration plants. In: International conference on future power systems. 2005. p. 6.
[150] Boukhanouf R, Godefroy J, Riffat SB, Worall M. Design and optimisation of a small-scale tri-generation system. Int J Low-Carbon Technol 2008;3(1):32–43.
[151] Lin L, Wang Y, Al-Shemmeri T, Ruxton T, Turner S, Zeng S, et al. An experimental investigation of a household size trigeneration. Appl Therm Eng 2007;27(2–3):576–85.

[152] Abdollahia G, Meratizaman M. Multi-objective approach in thermoenviro-nomic optimization of a small-scale distributed CCHP system with risk analysis. Energy Build 2011;43(11):3144–53.
[153] Canova A, Cavallero C, Freschi F, Giaccone L, Repetto M, Tartaglia M. Comparative economical analysis of a small scale trigenerative plant: a case study. In: Industry applications conference, 2007. 42nd IAS annual meeting. Conference record of the 2007 IEEE. 2007. p. 1456–9.
[154] Hossain AK, Thorpe R, Critoph RE, Davies PA. Development of a small-scale trigeneration plant based on a CI engine fuelled by neat non-edible plant oil. J Sci Ind Res 2011;70(8):688–93.
[155] Midwest CHP Application Center. Elgin Community College – 4.1 MW CHP application. Technical report. Midwest CHP Application Center; 2011.
[156] Southeast CHP Application Center. James H. Quillen VA Medical Center – 3.2 MW CHP system. Technical report. Southeast CHP Application Center; 2011.
[157] Midwest CHP Application Center. Spectrum health, butterworth campus – 3.8 MW CHP application. Technical report. Midwest CHP Application Center; 2011.
[158] Midwest CHP Application Center. Central Connecticut State University – 2.5 MW CHP application. Technical report. Midwest CHP Application Center; 2011.
[159] Northeast Clean Energy Application Center. Bradley Airport Energy Center – 5.8 MW CHP plant. Technical report. Northeast Clean Energy Application Center; 2011.
[160] Popli S, Rodgers P, Eveloy V. Trigeneration scheme for energy efficiency enhancement in a natural gas processing plant through turbine exhaust gas waste heat utilization, 2011. http://dx.doi.org/10.1016/j.apenergy.2011.11.038.
[161] Rodriguez-Aumente PA, del Carmen Rodriguez-Hidalgo M, Nogueira JI, Lecuona A, del Carmen Venegas M. District heating and cooling for business buildings in Madrid, 2012. http://dx.doi.org/10.1016/j.applthermaleng.2011.11.036.
[162] Balli O, Aras H, Hepbasli A. Thermodynamic and thermoeconomic analyses of a trigeneration (TRIGEN) system with a gas–diesel engine: part I – methodology. Energy Convers Manag 2010;51(11):2252–9.
[163] Balli O, Aras H, Hepbasli A. Thermodynamic and thermoeconomic analyses of a trigeneration (TRIGEN) system with a gas–diesel engine: part II – an application. Energy Convers Manag 2010;51(11):2260–71.
[164] Meybodi MA, Behnia M. Impact of carbon tax on internal combustion engine size selection in a medium scale CHP system. Appl Energy 2011;88(12):5153–63.
[165] Becker WL, Braun RJ, Penevb M, Melaina M. Design and technoeconomic performance analysis of a 1 MW solid oxide fuel cell polygeneration system for combined production of heat, and power. J Power Sources 2012;200:34–44.
[166] Midwest CHP Application Center. University of Michigan – 45.2 MW CHP application. Technical report. Midwest CHP Application Center; 2011.
[167] Pacific Region CHP Application Center. University of California at San Diego – 30 MW CHP system. Technical report. Pacific Region CHP Application Center; 2008.
[168] Midwest CHP Application Center. University of Illinois at Chicago – 57.4 MW CHP application. Technical report. Midwest CHP Application Center; 2011.
[169] Southeast CHP Application Center. UNC Chapel Hill – 32 MW cogeneration plant. Technical report. Southwest CHP Application Center; 2013.
[170] Gulf Coast Clean Energy Application Center. University of Texas, Austin – 137 MW (65 MW-peak) CHP application. Technical report. Gulf Coast Clean Energy Application Center; 2011.
[171] Southeast CHP Application Center. Vanderbilt University Plant Operations – 25 MW cogeneration plant. Technical report. Southeast CHP Application Center; 2010.
[172] Mago PJ, Chamra LM. Analysis and optimization of CCHP systems based on energy and environmental considerations. Energy Build 2009;41(10):1099–106.
[173] Cardona E, Piacentino A. A methodology for sizing a trigeneration plant in mediterranean areas. Appl Therm Eng 2003;23(13):1665–80.
[174] Cardona E, Piacentino A. Matching economical, energetic, and environmental benefits: an analysis for hybrid CCHP-heat pump systems. Energy 2006;47(20):3530–42.
[175] Cho H, Mago PJ, Luck R, Chamra LM. Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme. Appl Energy 2009;86(12):2540–9.
[176] Mago PJ, Fumo N, Chamra LM. Performance analysis of CCHP and CHP systems operating following the thermal and electric load. Int J Energy Res 2009;33(9):852–64.
[177] Wang J, Zhang C, Jing Y. Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China. Appl Energy 2010;87(4):1247–59.
[178] Smith A, Luck R, Mago PJ. Analysis of a combined cooling, heating, and power system model under different operating strategies with input and model data uncertainty. Energy Build 2010;42(11):2231–40.
[179] Wang J, Jing Y, Zhang C, Zhai Z. Performance comparison of combined cooling heating and power system in different operation modes. Appl Energy 2011;88(12):4621–31.
[180] Fumo N, Mago PJ, Smith AD. Analysis of combined cooling, heating, and power systems operating following the electric load and following the thermal load strategies with no electricity export. Proc Inst Mech Eng Part A J Power Energy 2011;225:1016–25.
[181] Liu M, Shi Y, Fang F. A new operation strategy for CCHP systems with hybrid chillers. Appl Energy 2012;95:164–73.
[182] Hashemi R. A developed offline model for optimal operation of combined heating and cooling and power systems. IEEE Trans Energy Convers 2009;24(1):222–9.
[183] Fumo N, Chamra LM. Analysis of combined cooling, heating, and power systems based on source primary energy consumption. Appl Energy 2010;87(6):2023–30.
[184] Cardona E, Piacentino A, Cardona F. Energy saving in airports by trigeneration. Part II: short and long term planning for the Malpensa 2000 CHCP plant. Appl Therm Eng 2006;26(14–15):1437–47.
[185] Fumo N, Mago PJ, Chamra LM. Emission operational strategy for combined cooling, heating, and power systems. Appl Energy 2009;86(11):2344–50.
[186] Fang F, Wang QH, Shi Y. A novel optimal operational strategy for the CCHP system based on two operating modes. IEEE Trans Power Syst 2011;PP(99):1–10.
[187] Zafra-Cabeza A, Ridao MA, Alvarado I, Camacho EF. Applying risk management to combined heat and power plants. IEEE Trans Power Syst 2008;23(3):938–45.
[188] Lozano MA, Carvalho M, Serra LM. Operational strategy and marginal costs in simple trigeneration systems. Energy 2009;34(11):2001–8.
[189] Nosrat A, Pearce JM. Dispatch strategy and model for hybrid photovoltaic and trigeneration power systems. Appl Energy 2011;88(9):3270–6.
[190] Rubio-Maya C, Uche-Marcuello J, Martínez-Gracia A, Bayod-Rújula AA. Design optimization of a polygeneration plant fuelled by natural gas and renewable energy sources. Appl Energy 2011;88(2):449–57.
[191] Rubio-Maya C, Uche J, Martínez A. Sequential optimization of a polygeneration plant. Energy Convers Manag 2011;52(8–9):2861–9.
[192] Buoro D, Casisi M, Pinamonti P, Reini M. Optimization of distributed trigeneration systems integrated with heating and cooling micro-grids. Distrib Gener Altern Energy J 2011;26(2):7–34.
[193] Li CZ, Shi YM, Huang XH. Sensitivity analysis of energy demands on performance of CCHP system. Energy Convers Manag 2008;49(12):3491–7.
[194] Lozano MA, Ramos JC, Serra LM. Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints. Energy 2010;35(2):794–805.
[195] Tuula Savola C-JF. MINLP optimisation model for increased power production in small-scale CHP plants. Appl Therm Eng 2007;27(1):89–99.
[196] Li H, Nalim R, Haldi PA. Thermal-economic optimization of a distributed multi-generation energy system—a case study of Beijing. Appl Therm Eng 2006;26(7):709–19.
[197] Rong A, Lahdelma R. An efficient linear programming model and optimization algorithm for trigeneration. Appl Energy 2005;82(1):40–63.
[198] Wang QH, Fang F. Optimal configuration of CCHP system based on energy, economical, and environmental considerations. In: International conference on intelligent control and information processing (ICICIP). 2011. p. 489–94.
[199] Sheikhi A, Mozafari B, Ranjbar AM. CHP optimized selection methodology for a multi-carrier energy system. In: IEEE Trondheim PowerTech. 2011. p. 1–7.
[200] Kavvadias KC, Maroulis ZB. Multi-objective optimization of a trigeneration plant. Energy Policy 2010;38(2):945–54.
[201] Wang J, Zhai Z, Jing Y, Zhang C. Optimization design of BCHP system to maximize to save energy and reduce environmental impact. Energy 2010;35(8):3388–98.
[202] Wang J, Jing Y, Zhang C, Shi G, Zhang X. A fuzzy multi-criteria decision-making model for trigeneration system. Energy Policy 2008;36(10):3823–32.
[203] Piacentino A, Cardona F. EABOT – energetic analysis as a basis for robust optimization of trigeneration systems by linear programming. Energy Convers Manag 2008;49(11):3006–16.
[204] Chicco G, Mancarella P. Matrix modelling of small-scale trigeneration systems and application to operational optimization. Energy 2009;34(3):261–73.
[205] Geidl M, Andersson G. Optimal power dispatch and conversion in systems with multiple energy carriers. In: Power systems computation conference. 2005. p. 1–7.
[206] Geidl M, Andersson G. Optimal power flow of multiple energy carriers. IEEE Trans Power Syst 2007;22(1):145–55.
[207] Geidl M, Koeppel G, Favre-Perrod P, Klockl B, Andersson G, Frohlich K. Energy hubs for the future. IEEE Power Energy Mag 2007;5(1):24–30.
[208] Geidl M, Andersson G. A modeling and optimization approach for multiple energy carrier power flow. In: IEEE Russia power tech conference. 2005. p. 1–7.
[209] Ghaebi H, Saidi MH, Ahmadi P. Exergoeconomic optimization of a trigeneration system for heating, cooling and power production purpose based on TRR method and using evolutionary algorithm. Appl Therm Eng 2012;36:113–25.
[210] Hueffed AK, Mago PJ. Influence of prime mover size and operational strategy on the performance of combined cooling, heating, and power systems under different cost structures. Proc Inst Mech Eng Part A J Power Energy 2010;591–605.
[211] Sclafani A, Beyene A. Sizing CCHP systems for variable and non-coincident loads: part 1 – load profiling and equipment selection. Cogener Distrib Gener J 2008;23(3):6–19.
[212] Shaneb OA, Coates G, Taylor PC. Sizing of residential μ CHP systems. Energy Build 2011;43(8):1991–2001.

[213] Harrod J, Mago PJ, Luck R. Sizing analysis of a combined cooling, heating, and power system for a small office building using a wood waste biomass-fired stirling engine. Int J Energy Res 2010;36(1):64–74.
[214] Ren H, Gao W, Ruan Y. Optimal sizing for residential CHP system. Appl Therm Eng 2008;28(5–6):514–23.
[215] Zhang B, Long W. An optimal sizing method for cogeneration plants. Energy Build 2006;38(3):189–95.
[216] Azit AH, Nor KM. Optimal sizing for a gas-fired grid-connected cogeneration system planning. IEEE Trans Energy Convers 2009;24(4):950–8.
[217] Rubio-Maya C, Uche J, Martínez-Gracia A. Selection and sizing procedure of polygeneration plants using mathematical programming. In: International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems. 2009. p. 587–94.
[218] Martínez-Lera S, Ballester J. A novel method for the design of CHCP (combined heat, cooling and power) systems for buildings. Energy 2010;35 (7):2972–84.
[219] Sheikhi A, Ranjbar AM, Oraee H. Financial analysis and optimal size and operation for a multicarrier energy system. Energy Build 2011;48:71–8.
[220] Hedman B. CHP: the state of the market. In: U.S. EPA combined heat and power partnership 2009 partners meeting and NYSERDA CHP roundtable. 2009. p. 1–51.
[221] International District Energy Association. Combined heat and power (CHP): essential for a cost effective clean energy standard. The International District Energy Association (IDEA); 2011.
[222] PEW Center on Global Climate Change. Cogeneration/combined heat and power (CHP). Technical report. PEW Center on Global Climate Change; 2011.
[223] MacLeay I, Harris K, Annut A. Digest of United Kingdom energy statistics 2011. Technical report. UK Department of Energy & Climate Change; 2011 [chapter authors].
[224] UK Department of Energy & Climate Change. Planning our electric future: a white paper for secure, affordable and low-carbon electricity. Technical report. UK Department of Energy & Climate Change; 2011.
[225] Kerr T. CHP and DHC in China: an assessment of market and policy potential. Technical report. International Energy Agency; 2008.